

CAETS ENERGY REPORT 2022

---

# TOWARDS LOW-GHG EMISSIONS FROM ENERGY USE IN SELECTED SECTORS



**CAETS**

International Council of  
Academies of Engineering  
& Technological Sciences

# TABLE OF CONTENTS

<b>Acknowledgment</b>	3
<b>Executive summary</b>	4
<b>Chapter 0. To set the scene</b>	13
<b>Chapter 1. Food and agriculture</b>	31
<b>Chapter 2. Buildings and Smart cities</b>	80
<b>Chapter 3. Oil and gas industry</b>	126
<b>Chapter 4. Chemical industry</b>	153
<b>Chapter 5. Cement industry</b>	169
<b>Chapter 6. Iron and steel industry</b>	215
<b>Chapter 7. Information and Communications Technologies</b>	263
<b>Chapter 8. Conclusions</b>	277
<b>List of authors , other contributors, reviewers (internal – external)</b>	280
<b>Annexes</b>	284
<b>Country analysis questionnaires</b>	285
Argentina	286
Canada	299
Croatia	311
France	320
Germany	334
Korea	344
Mexico	358
Nigeria	369
Spain	382
Sweden	394
Switzerland	403
United Kingdom	423
United States	433
<b>Sector analysis questionnaires</b>	456
Food and agriculture	457
Buildings and Smart Cities	463
Oil and gas industry	478
Chemical industry	485
Cement industry	488
Iron and steel industry	512

---

## ACKNOWLEDGEMENTS

This report was written by the members of the Energy Committee 2021-2022 and prepared by Yves Bamberger (Academician) supported by Dr. Wolf Gehrisch and Dr. Gaël-Georges Moullec of the National Academy of Technologies of France. Contributing authors where of great help in providing, beyond their engineering expertise, country-specific input for comparative analysis and publication.

This report has been produced with the financial assistance of the National Academy of Technologies of France, the National Academy of Engineering of the United States and CAETS. The views expressed herein can in no way be taken to reflect the official opinion of France and do not necessarily reflect the views of any CAETS member Academies.

This paper was discussed by the International Council of Academies of Engineering and Technological Sciences (CAETS) which agreed to submit the report to international journals and policymakers worldwide. The authors are grateful to the delegates for their input, comments, and suggestions. Any errors or omissions are the sole responsibility of the authors.

Publisher: CAETS

District of Columbia, USA

E.I.N. 52-2251297

An IRS Section 501(c)(3) organization

Web: [www.caets.org](http://www.caets.org)

# EXECUTIVE SUMMARY

## Table of Contents

---

Introduction .....	5
Who prepared this report and how? .....	5
Chapter 0: To set the scene .....	6
Chapter 1: Food and agriculture systems (FAS) .....	7
Chapter 2: Buildings and smart cities .....	8
Chapter 3: Oil and gas .....	8
Chapter 4: Chemicals .....	9
Chapter 5: Cement .....	10
Chapter 6: Iron and steel .....	10
Chapter 7: Information and Communications Technology (ICT) .....	11
Chapter 8: Conclusions .....	12

## Introduction

---

The Energy Committee of the International Council of Academies of Engineering and Technological Sciences (CAETS) has been tasked with reviewing existing technologies which can be used immediately to reduce greenhouse gas (GHG) emissions in seven key sectors: Food and Agriculture, Buildings and Smart Cities, Oil and Gas, Chemicals, Cement, Iron and Steel, Information and Communication technologies. Some of our conclusions could apply as well to other sectors like aluminium.

The deployment of these technologies would lead to deep emission reduction before 2040 which explains why the primary time frame of the report is 2020-2040. However, these technologies are not sufficient to meet net zero targets by mid-century. Therefore, the report also highlights research and development needs for new or improved technologies and demonstrations for the near ready technologies (RD&D).

While many cost-effective GHG mitigating technologies exist, the GHG emissions are still growing in many countries and worldwide. Indeed, many obstacles remain. The purpose of this report is not to analyse all of them. Undeniably, social and economic issues are critical to the global implementation of the Paris COP21 Agreement and subsequent COP meetings. These issues include: the impacts of world population growth, improvements to the quality of life in developing countries and regions, choices made by political and industrial leaders, etc., and they are important aspects. However, they are not within the scope of this report which is technical and it is meant to highlight technologies suitable for lowering GHG emissions, their advantages and limitations, and describe the technical, economic and cultural barriers that may exist.

The Report offers insights; conclusions and recommendations that should be useful for leaders of industry, governments, professional organisations (especially engineering organisations), non-governmental organisations, and citizens. The report is intended to provide clarity on the complex issues of our subject: what is possible for the next 20 years, where are the difficulties in the different sectors and how to overcome them.

## Who prepared this report and how?

---

The CAETS Academies of Technology and Engineering have three main characteristics: (1) their members are drawn from most sectors of activity, mainly from industry and academia; (2) they are collectively independent and neutral, without *a priori* advocating for any technology or sector; (3) their reports are evidence-based and resulting from exchanges based on facts and on their diversity of experience. Indeed, CAETS, with its different Member Academies from various countries, reflects this diversity. They are allowing an international approach illustrated by the numerous case studies and examples reproduced in this report prepared by more than 60 fellows and some external experts of more than 20 countries.

Given the time (15 months) and the resources available for the preparation of this report, we have looked for sectors with substantial emission levels and where the diversity of our active members could make the greatest contribution. In 2019, the seven sectors selected accounted for 73% of industry's CO<sub>2</sub> emissions (see Chapter 0, Fig. 0.2.) and around 60% of worldwide methane emissions. We did not select electricity generation as this topic was already largely covered by previous reports, neither the transport sector which could be an entire future study by its own.

In this report, each of the above sectors is the subject of a dedicated chapter prepared by a subgroup of the Committee and discussed by the Committee. Each chapter was reviewed by external and internal reviewers. The chapters do not claim to be exhaustive but present the main elements, as seen by the participants, and are accompanied with examples taken from different countries. During our meetings, held remotely via teleconferencing, key messages and recommendations emerged from our often-lively discussions. They are not necessarily original or new but should, nevertheless, be most useful to implement!

## Chapter 0: To set the scene

This chapter contains messages that are broadly applicable to all sectors. It presents the central role of low-carbon electricity in achieving emission reductions in the sectors considered. Electricity and heat are defined as low-carbon if they are produced with an average CO<sub>2</sub> content of less than 50 g per kWh over the life cycle of the installation. Low-carbon electricity is therefore mainly<sup>1</sup> produced by hydro, solar, wind and nuclear power.

As the different chapters of the report show, reducing GHG emissions, especially CO<sub>2</sub>, is in many cases achieved through the electrification of all or part of the energy used, whether for home heating and cooking or for industrial processes. The level of such reduction depends on the electricity mix, which shows the importance of decarbonising the production of electricity. Such an approach should not overlook low-carbon heat, including the direct thermal use of solar radiation, nor heat networks using low-carbon sources (e.g. waste, biomass) or waste heat from industry. Finally, it is shown that some industrial processes cannot be fully electrified, like cement production. The use of hydrogen – if it is produced with low-carbon electricity – may be part of the solution, but has to be produced at an affordable cost.

Another approach is to capture the CO<sub>2</sub> which is produced on industrial sites and to use it or to store it underground (Carbon Capture Utilisation and Storage, CCUS). Some industrial pilot projects are already in operation. The system used for the capture has to be adapted to the industrial process in question such as burning coal to produce electricity or iron, heating the required materials to prepare cement. Many demonstration and pilot projects are currently operating and planned worldwide. The solutions for the use of CO<sub>2</sub> seem to be very limited, whereas for storage they are already technically significant. The added costs and the societal aspects are real concerns, but the use of Carbon capture and storage (CCS) will certainly be needed to reach “net-zero” by the middle of the century.

Improvements in energy efficiency are about using less energy to heat, to move, to deform, to break, to transform, etc... This is almost always beneficial, although global rebound effects may reduce or annihilate the achieved GHG reduction. However, improving the efficiency of a system using fossil fuels can be more expensive and lead to higher emissions than replacing the system by another using low-carbon electricity. In other words, putting energy efficiency first is not synonymous with putting low emissions first: this is one of the key messages of this initial chapter. It illustrates the importance of using the right indicators when defining energy policies.

Another key message of this introductory chapter is the need for comprehensive and consistent policies to be enacted faster and implemented at lower cost. Examples include promoting the replacement of gas boilers with electric heat pumps in homes. Heat pumps should be available where needed, in sufficient quantities and at acceptable costs, installers should be qualified and widely available, and an economic model (which would include acquisition costs, operating costs, possible investment aids, etc.) linked to electricity tariffication should be proposed. Building regulations should be adapted, and appropriate public information campaigns should be developed. For a policy concerning new housing, it is also necessary to foresee training for architects, engineers, design officers and real-estate promoters. Such global programmes, involving millions of actors and stakeholders, require clear, understandable and stable policies for widespread implementation.

This highlights the problem of rapidly reducing emissions while time frames differ, as the lifespans of different technology systems vary significantly. For example, the typical time frame for changing a mobile phone is about 2 to 3 years, while it could be 15 years for a boiler, 30 to 100 years or more for a building, and 20 to 50 years for many factories. Comprehensive Life Cycle Assessment (LCA) helps to evaluate such questions as whether extending the lifespan of an existing appliance vs. replacing the appliance as soon as possible with another that emits less can reduce total emissions.

<sup>1</sup> Biomass is the subject of divergent opinions within the Committee, because of the emissions it produces when burned. Another issue, controversial and outside the scope of this report, is its other possible uses for food, biofuel and consequent competition for land use

This introductory chapter also addresses the rebound effect, recycling, the role of information and communications technologies, and education and training, which play a key part in the development of all areas of human activity. Lastly, this chapter is complemented by an Appendix on three strong levers for reducing emissions: heat pumps, which are not yet widely known; life cycle analyses, which are not used adequately; and hydrogen, whose potential is often either underestimated or overestimated.

## Chapter 1: Food and agriculture systems (FAS)

---

This chapter describes how the FAS has gone through deep transformations to feed the world, which has generated sustainability concerns that call again for a profound transformation acknowledging climate change, conflicts, disruptions, and wars that globally impact the FAS. Since the FAS is responsible for 25 to 33% of the GHG emissions (depending on the definition), reduction of its GHG emissions is an essential element of the FAS transformation but is not the only one; it implies trade-offs among diverging sustainability objectives and across the various scales of time and space and calls for strengthening the capacity to address such trade-offs through evidence and arbitration mechanisms.

Science and technology have been key in generating the past transformation of food systems and will remain so. Yet innovation does not always contribute to sustainable development! At the same time, in many countries, there is currently a call for significantly reducing the consumption of animal-based foods, especially from the younger generation, for a healthier diet with less meat. There remains much controversy, for example regarding the mobilisation of disruptive technologies (such as alternative protein foods, 3D-printed foods, aquaculture / aquaponic systems, and advanced greenhouses including vertical farms) because of entrenched long-standing traditional local practices, on the one hand, and concerns about increasing concentration in an industrialised agri-food sector, on the other hand.

The chapter describes avenues for reducing the emissions of two important GHGs produced by the FAS: methane from ruminant livestock and from rice cultivation, and CO<sub>2</sub> along the supply chain from farm to fork especially through energy efficiency and electrification. The chapter insists on the importance of assessing the potential contribution of each specific technology taking into account the local, ecological, economic, and social contexts and the way technology may be applied in practice. Some examples are developed to illustrate this need: 'digital agriculture', which involves advanced sensors, artificial intelligence, data integration, big data, drones, robots, and tracking technologies.

The potential role of biotechnology and nanotechnology to reduce GHG emissions in the FAS, the co-location of solar photovoltaic ('agrivoltaic') and wind turbines with agricultural activities, and the use of biomass for energy production, are also described. A strong recommendation is made to only use bioenergy in situations where it does not compete with food production.

The chapter suggests developing an enlarged database on and analysis of the different technologies and their local uses. It insists on the necessity to develop strong investment in research and expertise, not only for the development of technologies but, also, as is the case in other sectors, but especially for FAS, for their adaptation to local contexts in order to achieve real improvements and for the assessment of their footprint. Finally, the FAS as a system of systems requires the design and acceptance of an array of different approaches, valuing scientific evidence as much as possible.

## Chapter 2: Buildings and smart cities

---

Like the previous chapter on the FAS, this chapter deals with a high emitting sector (some 37% of the world CO<sub>2</sub> emissions in 2019), where the local conditions are very important. Decarbonisation addresses residential and non-residential buildings, including the construction and operation of new buildings and the operation of existing buildings. Because of their lifespan, the retrofitting of existing buildings plays a major role. Besides the energetic quality of the building envelope and the equipment used, occupant behaviour has a major influence on energy consumption.

To design low-carbon, low-energy buildings, the Committee recommends an energy hierarchy principle: first, choose low-carbon materials and energy sources and second, apply the most efficient equipment (taking into account their affordability). Applying this principle to retrofitting in order to reduce the emissions in the most affordable way requires evaluating the right level of insulation and the implementation of a low-carbon heating system.

Photovoltaic (PV) or solar thermal panels are more and more often installed. For buildings where the auto-generation of energy is not an option or insufficient, as it is generally the case in cities, electrification using low-carbon electricity from the grid remains the most efficient decarbonisation solution. This applies in particular to the 4 basic energy-consuming needs: heating, cooling, heating water and cooking. For each, the chapter recommends solutions.

Two important points should be mentioned here: (a) the increasing importance of cooling since more than half of the global population lives in countries that require space cooling and because climate change is increasing the need for cooling; (b) today, in many emerging countries, biomass burning in low efficient and dangerous cooking stoves is still in use and needs to be replaced by more efficient appliances.

Increasing electrification prompts the question of flexibility in electricity consumption, which refers to its ability to be interruptible and adjustable, e.g. shifting the use of a water heater or a washing machine to times when there is much (or cheap) electricity, for example in the middle of a sunny day when photovoltaic is generating lots of electricity. The flexibility in the consumption will have an increasing role in regard to the insertion of intermittent renewables.

Another aspect is the decarbonisation of urban energy supply systems, including not only the district heating systems but also, and increasingly so, the district cooling systems. The permanent difficulty to equate the need for heat and its production suggests developing inter-seasonal heat storage, an option not much used today. This leads to a brief presentation on smart cities – principally on the energy needs of buildings. We do not discuss other aspects of smart cities, like overall energy management, transport, water supply, and health care.

The path to a sustainable stock of buildings must be facilitated by an integrated policy package adapted to local conditions. Furthermore, additional efforts in education and training are needed. Case studies are presented, one on the decarbonisation of a slum in Buenos Aires and two on district heating networks in China.

## Chapter 3: Oil and gas

---

This chapter reminds us first that the world still heavily relies on fossil fuels. In 2019, fossil energy sources provided more than 84% of global primary energy demand, and oil and natural gas account for more than 57% of the world's total. The use of crude oil and natural gas has been increasing worldwide, especially in less developed countries, and will likely continue doing so in the near- to medium-term future which is the focus of this report. Regardless of future needs for oil and gas for energy purposes, non-energy uses, especially for the chemical industry, will probably increase.

For this reason, it is important to examine whether the oil and gas industry can reduce its GHG emissions in all phases of oil and gas production, transport, refining, and distribution. In 2019, while 76% of the emissions from oil and gas was produced by their consumption by end users, 24% resulted from oil and gas industry processes. This 24% represented around 8% of the worldwide GHG emissions, i.e. about 2.65 GtCO<sub>2</sub> and around 2.5 GtCO<sub>2e</sub> from methane (CH<sub>4</sub>).

The current cumulative investments in the oil and gas industry amount to trillions of dollars and facilities have life spans of decades. Most of these facilities tend to be highly optimised for the types of oil and gas they receive

and the products their markets require. This makes it challenging to apply major changes on a global scale and at a rapid pace. Nevertheless, the future oil and gas industry will be significantly different from the present one.

The Committee recommends a strong emphasis on reducing the flaring of methane and fugitive methane emissions in all phases of oil and gas production, transport, and refining/processing. Technologies to abate methane emissions/leaks are available and many are already cost-effective. The IEA estimates that 45% of emissions can be abated at no cost under 2021 gas prices.

The oil and gas industry uses oil and gas as energy sources for its own needs, in particular, to produce heat. The Committee recommends exploring the increased electrification of the oil and gas industry to substitute for the direct heating and cooling of process streams. To achieve this, operators of oil and gas facilities should consider switching to electric options where feasible and where they are likely to have a positive impact on lowering GHG emissions. Furthermore, it is suggested to explore additional steps to lower CO<sub>2</sub> emissions from the exploration and production sectors through the reduction of flaring and the implementation of efficiency improvement and new technologies.

The chapter also highlights two other important points: 1) the need for greater emphasis on using and improving LCAs (Life Cycle Assessment models) in the oil and gas industries, and 2) the continuous evaluation and development of the potential of CCUS opportunities for oil and gas operations.

## Chapter 4: Chemicals

The chapter first emphasises that most of the existing thousands of chemical products are manufactured with ‘primary’ chemicals obtained by using (and not by combusting) feedstock produced by the oil and gas industry. The chapter is focused on the analysis of GHG emissions resulting from the production of the four highest-tonnage primary products (ethylene, propylene, ammonia and methanol), acknowledging that additional emissions result from their derived products.

As the production of these chemicals entails specifically high energy requirements, the chemical sector was responsible in 2019 for 15% of the total GHG emissions (8.4 GtCO<sub>2</sub>) of the overall industrial sector. With 5% of this total, ammonia is the largest contributor of all chemicals. Over the next 20 to 30 years, economic and population growth will continue pulling demand, as for the last 20 years. As a result, it is imperative to reduce the GHG emissions in the sector. It is important to keep in mind that such emissions may result not only from the energy source used for the production processes but also from the chemical reactions themselves.

As a particularly complex, integrated, capital- and skills-intensive industry, with many long-lasting assets, the chemical sector faces enormous challenges in the transition to net zero carbon. There is no single or simple solution available today to decarbonise the chemical industry, but there are nevertheless important avenues that can guide the industry immediately towards its decarbonisation goals. Among those avenues, the Committee recommends the reuse of products (mainly plastics), the recycling of other carbon-based materials, and the reduction in the specific consumption of nitrogenous fertilisers by increasing application efficiency.

Further recommended actions include the electrification of process heating with low-carbon electricity, in particular in steam cracking, to replace coal and natural gas, which are currently used. Moreover, it is recommended to modify the chemical processes in order to substantially reduce the emissions, if not completely – by increasing, for example, the use of ethane in the production of ethylene, or replacing coal with natural gas in the production of methanol. Concerning ammonia synthesis, which is using hydrogen, the recommendation is to develop large-scale low-carbon hydrogen production via electrolysis using low-carbon electricity; alternatively, if hydrogen is produced from fossil fuels, it has to be with CCUS. CCUS will be required not only for the production of hydrogen but also for other chemicals-producing facilities to meet the 2050 decarbonisation objectives.

Due to the chemical industry’s many connections with the entire economy, from its raw materials to its products, it is recommended to systematically use Life Cycle Analysis for the chemical products at global levels.

## Chapter 5: Cement

Cement is widely used in the construction sector (buildings, bridges, dams, etc.). In itself, its production is a highly energy-intensive process and by far the most CO<sub>2</sub> emitting phase of the cement industry, from raw materials to ready-to-use construction materials, such as for example concrete. For this reason, the chapter on cement is focused on its production.

As a first step, the chapter presents the general correlation between GDP growth and cement demand in different countries and concludes that demand growth will be mostly driven by developing countries. This will apply in particular in areas such as infrastructure and real estate. In 2019, the worldwide cement industry was responsible for around 7% of global carbon emissions (some 2.5 GtCO<sub>2</sub>). It is thus one of the largest CO<sub>2</sub>-emitting sectors. Its decarbonisation is therefore crucial.

Cement is a versatile and durable material mostly produced with readily-available local resources such as limestone, clay and marl. Around 50% of the CO<sub>2</sub> emissions from cement production are due to calcination, the chemical reaction liberating CO<sub>2</sub> from limestone and producing the 'clinker', the base of cement. Around 40% of the emissions are due to the burning of fossil fuels used to reach the 1 450°C required by the calcination to take place.

Worldwide, coal represents 70% of the emissions of the fossil fuels used for calcination, which is the central and most energy-demanding process. Alternative fuels such as carbon-containing industrial wastes or biofuels can be used and are described. The use of low-carbon hydrogen, if available, is also advocated. Furthermore, it is recommended to increase energy efficiency and proceed with electrification where possible, as well as to increase heat recovery, which is not yet widespread.

Modifying the composition of the basic raw materials, replacing for example some limestone with fly ash etc., can reduce CO<sub>2</sub> emissions. This may modify the properties of the resulting cement, positively or negatively, allowing the development of new types of cement for different purposes. Notwithstanding, this will not entirely solve the CO<sub>2</sub> emission problem. Therefore, CCUS will be needed, although this is still not a completely proven technology for cement and will increase the cost of cement.

Existing solutions and policies for cement production in different countries are described and completed by five case studies from India, Norway, Belgium, Canada and China. Clear, stable, and holistic public policies, as well as incentives promoting a reduction in CO<sub>2</sub> emissions, are recommended. The large-scale deployment of already mature solutions is encouraged. The Committee urges close cooperation between the cement and other industries to benefit from the use of different wastes, non-recycled elements, granulated slag from steel blast furnaces, etc. either as fuel substitutes or alternative raw materials.

The Committee stresses the importance of R&D efforts to further reduce the GHG footprint of cement making and encourages the development and industrial demonstration of related technologies. Exploration in the area of CCUS and CO<sub>2</sub> mineralisation in some rock formations, in order to obtain affordable ways to reach deep decarbonisation, is also encouraged.

## Chapter 6: Iron and steel

Like for cement, the demand for steel is expected to increase as the global population grows and nations around the world seek to improve their standards of living: steel is a necessary and difficult to replace material in a wide range of applications.

The chemical reduction of iron ore requires much energy. Thus, the production of steel, which is iron with no more than 2% carbon and some additives to adjust its properties, is by nature energy intensive. The first step of the process, which needs the most energy, is to obtain iron from iron oxide, the second is to transform iron into steel. When using scrap as the feedstock, the first step is not needed: this shows the merit of recycling!

Coal is the dominant energy source in the most frequent production processes, the 'BF-BOF' (Blast Furnace / Basic Oxygen Furnace) route, which, in 2020 provided 73% of worldwide steel production. A second used route is the 'EAF' (Electric Arc Furnace) route, employing both scrap and/or Direct Reduced Iron (DRI) using gas. The EAF route, using electricity, represents 26% of the worldwide steel production. As a consequence, in 2020, the emissions from the steel industry were of the order of 2.6 Gt of CO<sub>2</sub>, representing around 8% of global anthropogenic CO<sub>2</sub> emissions.

Considering the urgency of the reduction of CO<sub>2</sub> emissions and the lifetime of many existing facilities, the Committee recommends implementing every possible and economically affordable, even marginal, reduction of CO<sub>2</sub> emissions for existing steel plants by increasing energy efficiency, utilisation of residual energies, partial electrification for heating, use of biomass, better control, etc.

To eliminate CO<sub>2</sub> from the process, although there is no single final scenario, direct reduction of iron ore (DRI) using low-carbon hydrogen, followed by Electric Arc Furnace (EAF), seems to be one of the most viable options and a long-term solution to achieving carbon-neutral steel production. Various processes are under development and at pilot scale: their economic viability will certainly be proven before 2030. The availability and cost of such low-carbon hydrogen and low-carbon electricity will be key for the massive implementation of these processes.

The chapter contains case studies describing pilot projects from different countries (and steelmakers) including China, Korea, Japan, Sweden, Finland, the United States of America, France, and Germany.

It is worth mentioning that CCS in combination with steel production has not yet been proven on an industrial scale. This could change during this decade with several projects at different stages of implementation in different countries.

Needing less energy to produce 'new' steel, the utilisation of ferrous scrap is expected to gradually increase. The Committee recommends continuing to expand the use of steel scrap, even if there will not be enough scrap available to replace iron ore. It could be facilitated through the adoption of common rules and specifications but also the development and implementation of new scrap processing technologies to improve impurity removal.

Steel production has the potential of becoming low-carbon in the future. Nevertheless, as the chapter concludes, many challenges remain: the scale and efficiency, availability of low-carbon hydrogen and electricity, investment needs, stranded assets and return of capital, approvals from regulators and policymakers, skill shortages, etc. The Committee recommends incentivising pilot projects, simplifying and accelerating permitting procedures, and ensuring competition while sharing experiences.

## Chapter 7: Information and Communications Technology (ICT)

The chapter first describes the current situation in this industry sector. On the one hand, ICT is increasingly ubiquitous, consumes more and more energy and induces more and more emissions. On the other hand, ICT contributes to human development and many other activities while, in some cases, reducing energy consumption and GHG emission in other domains. One striking example, witnessed during the COVID-19 period, is the development of videoconferencing to substitute for travelling and human mobility. Indeed, it is a public policy dilemma to simultaneously promote expansion in ICT facilities and reduction in GHG emissions. Another important message of the chapter is that data on the impact of ICT in terms of energy consumption and emission is largely imprecise and lacking.

ICT systems (laptops, servers, network routers, wireless transmission systems, etc.) consume electricity, most of them around the clock. Manufacturing the devices requires electricity and/or energy not only in the manufacturing process but also in the extraction/production of the required minerals and products, and this is generally not accounted for in consumption estimates. The 2019 worldwide electricity consumption from the ICT sector was estimated at 2 000 TWh (8.5% of total electricity consumption), corresponding to some 3% of CO<sub>2</sub> emissions, half of it accounting for equipment manufacturing. This consumption has been steadily increasing, even though the energy efficiency of ICT equipment, measured in bit per Wh, has been increasing: we can now store, process and transmit much more data for the same unit of energy. However, new developments such as artificial intelligence (AI), 5G and cryptocurrencies will clearly lead to further increases in electricity use and CO<sub>2</sub> emission.

The chapter does not cover manufacturing/decommissioning but is focused on ICT's operational points. One of them is Data Centre consumption and, in that respect, the case study of Ireland describing the consequences of having simultaneously attracted numerous data centres and developed intermittent electricity is presented.

Data Centers being at the core of the issues related to ICT electricity consumption, the first recommendation is to continue improving their efficiency through relevant measures and effective management practices. The second recommendation relates to the significant increase in energy consumption associated with the expan-

sion of 5G and suggests initiatives to reduce such consumption. The third recommendation touches on forthcoming ICT system developments, as an increasing number of small data centres will constitute the so-called ‘edge’ system: evaluating the impacts of architectural choices on electricity consumption and CO<sub>2</sub> emissions for these new deployments still needs more research.

The final recommendation of the chapter tackles the lack of reliable data by proposing the development of metrics and systematic studies on energy consumption and emissions in the ICT sector. Once gathered, these data should also be made widely available.

## Chapter 8: Conclusions

The Conclusions reminds us all of how urgent it is to act without further hesitation, and thus advocates the massive and rapid deployment of the available technologies described in the different chapters. It is not only about investing money for transforming the different sectors, but also about investing in people and expertise, by developing holistic views. Many difficulties and conflicting interests as well as conflicting priorities between sustainable objectives stand in the way of a rapid implementation of these recommendations.

**We, the members of the CAETS Energy Committee are deeply convinced that these difficulties are surmountable and possibilities exist to act far more rapidly, inclusively and efficiently through comprehensive global approaches to reduce GHG emissions, and this is what the report calls for. We hope that the key messages from the Chapter 0 and the messages and recommendations from the seven chapters will effectively contribute to reduce GHG emission. We are also convinced that our respective Academies, as well as the CAETS as a whole, could be better involved and more actively mobilised to advise policymakers and industry leaders in order to reach the 2030-2050 goals on GHG emissions.**

## Annexes

The annexes contain information by country at the national level and/or, for some countries, on the sectors studied in the report, based on replies to a questionnaire. The information at the national levels is in most cases based on the data of the International Energy Agency, completed by local data and comments prepared by the members of the Academy and/or by their members participating in the preparation of the report.

### Note for the reader

Due to having received responses from many countries we have tried to homogenise the representation of numbers. Nevertheless, some inconsistencies will have remained. The reader may thus find 20 000 or 20,000 for twenty thousand for example. For decimal, he may find 1.23 but also 1,23 for example.

# CHAPTER 0. TO SET THE SCENE

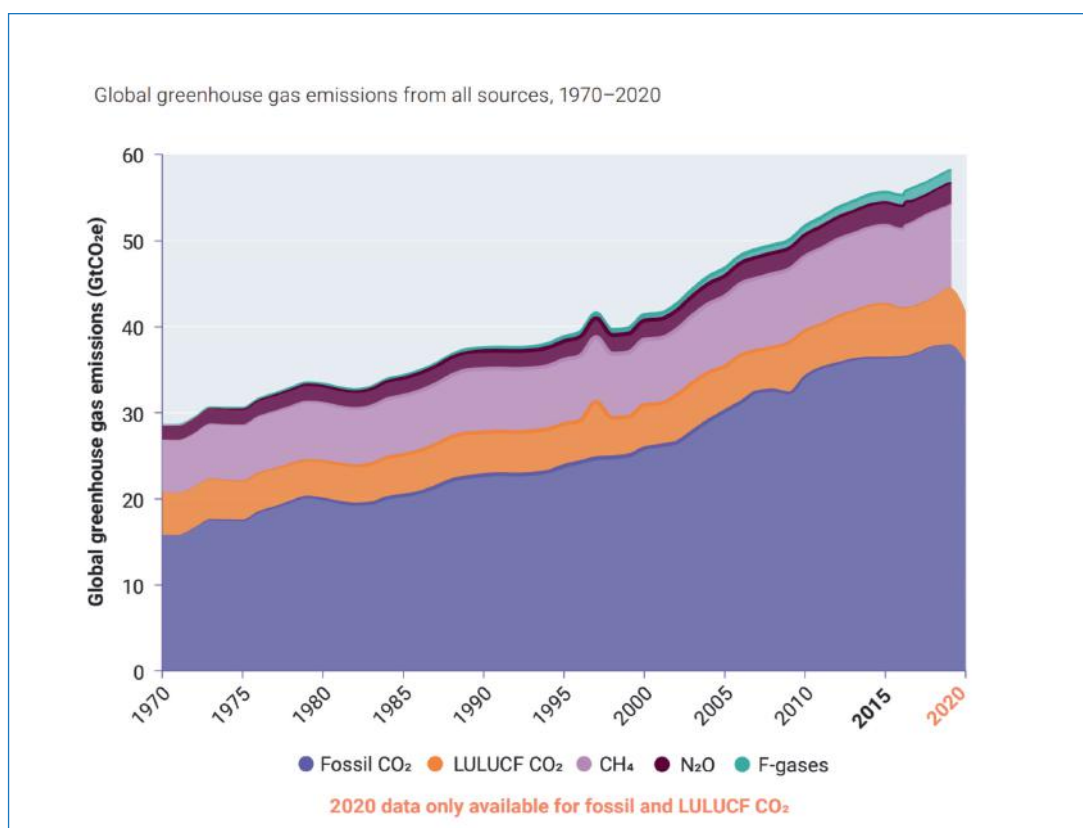
Chapter prepared by **Yves Bamberger** and adopted by the Energy Committee

## Table of Contents

<b>1.</b>	<b>Context, scope and methodology of the report</b>	<b>14</b>
<b>2.</b>	<b>The central role of low-carbon electrification</b>	<b>18</b>
<b>3.</b>	<b>Fifteen general comments</b>	<b>20</b>
	Low-carbon available technologies	20
	Local adaptation of some technologies	20
	Energy efficiency and the rebound effect	20
	Life Cycle Assessment	21
	Recycling, circular economy and the reduction of GHG emissions	21
	Importance of holistic approaches	21
	Different impacts of ICT	21
	Stability and predictability of regulatory changes	21
	Importance of metrics and data sources	22
	Impact of size on the transition in capital-intensive sectors	22
	Benchmarking	23
	Synergies between uses and resiliency	23
	RD&D	23
	Skills and competencies	23
	Leadership, collaboration, networking and social issues	24
	<i>Annex</i>	
	<b>Three transversal levers for the transitions: heat pumps, hydrogen, LCA</b>	<b>24</b>
1.	Heat pumps: a key technology family for the transition	24
2.	Hydrogen: a key vector to complete electricity	26
3.	Life Cycle Assessment (LCA): a key methodology to analyse emissions	29

## 1. Context, scope and methodology of the report

The reports of the Intergovernmental Panel on Climate Change (IPCC) issued during the 2021-2022 period show that it is becoming ever more urgent to act in order to contain climate change and other related global issues. Despite the COP26 conference, numerous announcements from governments, trillions of investments in efficiency and renewable sources, the major greenhouse gases (GHGs), especially CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and SF<sub>6</sub>, keep increasing as shown in Fig. 0.1. (in this figure, data for 2020 is only available for fossil CO<sub>2</sub> and Land Use, Land Use Change and Forestry (LULUCF), but not for Fluorinated Gases (F-gases), CH<sub>4</sub> or N<sub>2</sub>O). The result is that in 2019, the annual average concentration of CO<sub>2</sub> in the atmosphere reach 410 ppm, compared to 280 before the industrial age (See IPCC - Climate change 2021 - The physical science basis - Summary for policymakers).



**Fig. 0.1.** Global GHG emissions from all sources  
 Source: Emissions Gap Report 2021: The Heat Is On, page XVII  
<https://www.unep.org/resources/emissions-gap-report-2021>

The CAETS<sup>1</sup> are committed to addressing these highly complex and systemic issues, to which technology is only one of the key elements, although an essential one. This is why we have endeavoured to write this report. The reader will see that many of the technologies that can mitigate present global climate change are already available and affordable, or could be made so, and may be deployed immediately as soon as the political, economic, and societal contexts are sufficiently aligned and stable.

*For this reason, our report is focused on the time period 2020-2040 to illustrate what may be possible right now.*

However, some considerations in our report extend to beyond 2040 and some even extrapolate beyond existing technologies since the development and implementation of new technologies will open new possibilities to help the world meet the net-zero goals. Continuous support and funding for Research and Development (R&D) are thus critical.

The Council of Academies of Engineering and Technological Sciences (CAETS) provides its more than 30 worldwide Member Academies and their individual Fellows with the opportunity to enrich their approaches

<sup>1</sup> <https://www.newcaets.org/>

beyond their respective national contexts. CAETS enables comparing solutions, sharing best practices and making suggestions to the respective public authorities of the Member Academies. The Academies do not lobby for any specific technology or special interest but aim to make recommendations based on evidence rather than self-interest, ideology, or philosophical motivations. The composition of the Academies and the diversity of their Members, some coming from the Industry, some other from the academic world or other sectors, help us elaborate evidence-based reports, which is of utmost importance for policy-makers, industrial leaders, and the general public in an area where ‘wishful thinking’ and ‘fake news’ are often present.

In its past reports<sup>2</sup>, the CAETS Energy committee first analysed aspects of energy generation (2018), then the integration of intermittent sources (2020). As the other side of the energy equation: how is it used, had not been addressed so far, this topic has been chosen for this 2022 report.

Many international reports produce ‘scenarios’ or present ‘roadmaps’<sup>3</sup> to net-zero GHG emissions by 2030, 2050 or 2060, for example, one reference being the well-known 2021 Net-Zero IEA Roadmap . International sectorial associations are also describing how their respective sector will reduce GHG emissions. At the national level, in particular in connection with the Paris Agreement, many countries have also presented national ‘roadmaps’.

We have chosen to highlight some of the most GHG-intensive sectors of the global economy in this report and to explore feasible approaches to GHG emissions reduction. Our report is not strictly limited to the technical dimensions of the issue since other dimensions as well as holistic approaches are required to move on from discussing to acting.

We have opted to focus on sectors that are energy and capital intensive, with presently high GHG emissions, and for which the diversity of member Academies is an asset to provide relevant answers, comments and recommendations.

We did not include some important sectors in this study, as we had to choose those in which our limited resources could be put to the best use. Therefore, we decided not to consider the sectors of transport, aluminium and paper. Along these lines, the chapters included in this report are the following:

- Chapter 0.* To set the scene
- Chapter 1.* Food and agriculture
- Chapter 2.* Buildings and Smart Cities
- Chapter 3.* Oil and gas industry
- Chapter 4.* Chemical industry
- Chapter 5.* Cement industry
- Chapter 6.* Iron and Steel industry
- Chapter 7.* Information and Communications Technologies
- Chapter 8.* Conclusions
- Annexes* Country analysis questionnaires

<sup>2</sup> <https://www.newcaets.org/statements-reports/caets-reports>

<sup>3</sup> <https://www.iea.org>

Fig. 0.2. below shows the 2019 GHG emissions produced by the major sectors, in particular by the sectors covered in this report (McKinsey Sustainability Insights 2021).

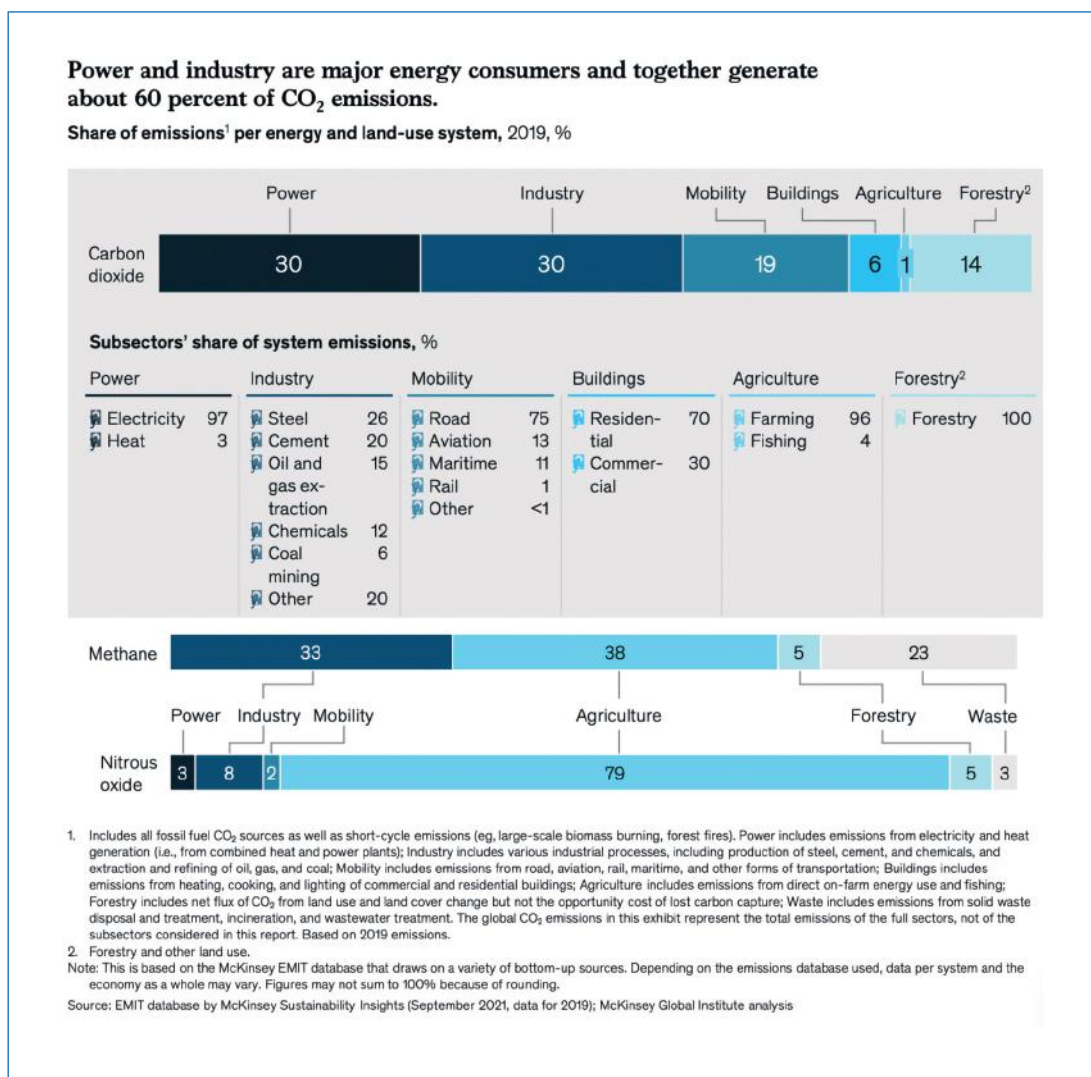


Fig. 0.2. Percentage of CO<sub>2</sub> emissions by sector, 2019

Exhibit from "The net-zero transition. What it would cost, what it could bring", January 2022, McKinsey & Company, [www.mckinsey.com](http://www.mckinsey.com).

Copyright © 2022 McKinsey & Company. All rights reserved. Reprinted by permission.

<https://www.mckinsey.com/~media/mckinsey/business%20functions/sustainability/our%20insights/the%20net%20zero%20transition%20what%20it%20would%20cost%20what%20it%20could%20bring/the-net-zero-transition-what-it-would-cost-and-what-it-could-bring-final.pdf>

The report is organised as indicated below.

- This introductory chapter (*Chapter 0.*) is focused on the increasing role of electricity and provides common comments concerning most sectors to facilitate decisions and actions by policy-makers, industrial and academic leaders.
- Each of the seven chapters in this report describes one sector. The chapters are not exhaustive monographs on their subject. They do not examine the potential for growth or contraction of their sector. Their focus is on scope 1 and scope 2<sup>4</sup>, as defined in the studies on Climate Change<sup>5</sup>. They highlight the main elements on the potential pathways to reduce GHG emissions as seen by the Members of our Committee, using *currently available* technologies and existing ‘low-hanging fruit’ for ‘non-regret’ strategies, some lessons learned or case studies and, where appropriate, potentially disruptive technologies.
- Finally, *Chapter 8.* draws conclusions and summarises our key findings.
- The annexes contain country specific data on energy use, GHG emissions, information on decarbonisation strategies, and further elements for some selected sectors.

### *How was this report prepared?*

After the validation of a scoping paper and a working process suggested by the Committee Chairman, the CAETS Member Academies were invited to propose participants to the Committee and to its Working Groups. The list of the more than 60 authors from 20 countries is given at the end of the report.

The working process was organised along the following two parallel lines.

1. Seven Working Groups, generally led by two co-chairs from different continents, were organised and responsible for the drafting of one chapter each. Sometimes they have invited external experts (the list of these experts can be found at the end of the report). The Working Groups also presented the progress of their work in seminars organised by the Energy Committee.
2. In total, the chairman organised such Energy Committee Seminars from February 2021 to June 2022, where transversal issues were presented, proposals by the Working Groups discussed and suggestions for achieving further progress made. All members of the Working Groups were invited to the seminars, held in two-hour sessions, twice a day (morning and afternoon, Central European Time) to facilitate the participation of members in different time zones, on two consecutive days.

A complete version of each chapter was produced by the end of May 2022 and then sent to internal reviewers (members from one Working Group (WG) reviewing the chapter of another WG) and external reviewers (list at the end). The reviewers’ comments and suggestions were discussed and taken into account by the WGs from 20 June to 10 July 2022, under the leadership of the WG’s Co-chairs, before validation by the participants. The revised version of the whole text was sent for editing to ensure as much consistency as possible for a text written by many hands! The text was then sent to the Academies for endorsement.

The process was supported by NATF’s team lead by the Committee Chairman Pr. Yves Bamberger (Academician) supported by Dr. Wolf Gehrisch and Dr. Gaël-Georges Moullec.

<sup>4</sup> Scope 1, Scope 2, emissions: Emissions responsibility as defined by the GHG Protocol, a private sector initiative. ‘Scope 1’ indicates direct greenhouse gas (GHG) emissions that are from sources owned or controlled by the reporting entity. ‘Scope 2’ indicates indirect GHG emissions associated with the production of electricity, heat, or steam purchased by the reporting entity.

<sup>5</sup> See for example: [https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc\\_wg3\\_ar5\\_annex-i.pdf](https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-i.pdf) and <https://ghgprotocol.org/standards>

## 2. The central role of low-carbon electrification

The focus of the report is the reduction, as soon as feasible, of GHG emissions from energy uses in the seven sectors it covers. This includes all types of energy uses in the sectors including: heating, cooling, manufacturing, processing, data handling, etc.

Today, fossil energy sources are largely used in industry and remain the main source for electricity generation: thus, *energy efficiency improvements*, i.e. the use of technologies that contribute to lowering energy/electricity consumption, directly reduce GHG emissions. When electricity has a low-carbon content, i.e. is quite entirely produced via renewable energy or nuclear power, increasing or decreasing its consumption will have less impact on CO<sub>2</sub> emissions. This is likely to happen at a different pace in each country.

### *What is low-carbon electricity?*

The CO<sub>2</sub> content of electricity, also known as the CO<sub>2</sub> intensity of electricity, is usually characterised by the number of grams of CO<sub>2</sub> produced to obtain 1 kWh of electricity. See for example <https://www.iea.org/data-and-statistics/data-product/emissions-factors-2021>.

With electricity produced through hydropower, wind, solar or nuclear energy, CO<sub>2</sub> content is equal to zero if only emissions for operation are considered, and not the complete cycle for the plant and the fuel: (a) upstream (e.g., material acquisition and plant construction), (b) combustion (where applicable), (c) operation and maintenance, (d) plant decommissioning and fuel disposal/recycling. Taking these phases into consideration, CO<sub>2</sub> content is generally estimated to be between 10 gCO<sub>2</sub>/kW and 50 gCO<sub>2</sub>/kWh. See for example analysis by the US National Renewable Energy Laboratory (NREL) [<https://www.nrel.gov/analysis/life-cycle-assessment>].

According to IEA, <https://www.iea.org/data-and-statistics/data-product/emissions-factors-2021>, the average CO<sub>2</sub> content of electricity worldwide was:

- 950 gCO<sub>2</sub>/kWh for coal, with plants below 900 gCO<sub>2</sub>/kW and others at 1 100 gCO<sub>2</sub>/kWh,
- 430 gCO<sub>2</sub>/kWh for natural gas, with plants around 350 gCO<sub>2</sub>/kW and others at 550 gCO<sub>2</sub>/kWh.

Taking into account the complete cycle, some 10 g have to be added for natural gas plant, some 20 g for coal plants.

**In this report, the term low-carbon energy implies emitting less than 50 gCO<sub>2</sub>/kWh for electricity as well as for heat.**

While energy efficiency is often among the ‘low-hanging fruit’, it does not lead to “zero emissions”. Comparing the decrease of GHG emissions resulting from the introduction of specific energy-efficient technology (with its associated cost) with other available solutions, such as replacing the energy vector (gas with electricity for example), reveals key variables for each outcome.

Four principal options, which may possibly be combined, are currently available to achieve as soon as practicable low GHG emissions:

1. When feasible, replace fossil sources by *directly* using low-carbon sources: direct use of solar energy to heat water for example;
2. If 1 is not feasible, replace fossil sources with low-carbon heat or low-carbon electricity (hydropower, solar and other renewable energy, or nuclear energy);
3. If 1 or 2 are not feasible, use low-carbon (‘green’) hydrogen (see *Annex to Chapter 0*. below, second section), which often means indirectly using (even more) electricity;
4. In hard-to-abate industries, emissions arise from the process itself (in the cement industry for example) and cannot be simply reduced by the use of low carbon electricity or hydrogen. If the process itself cannot be decarbonised, carbon capture and storage (CCS) may be the solution, if it is proven to be cost-effective and practical in a specific location.

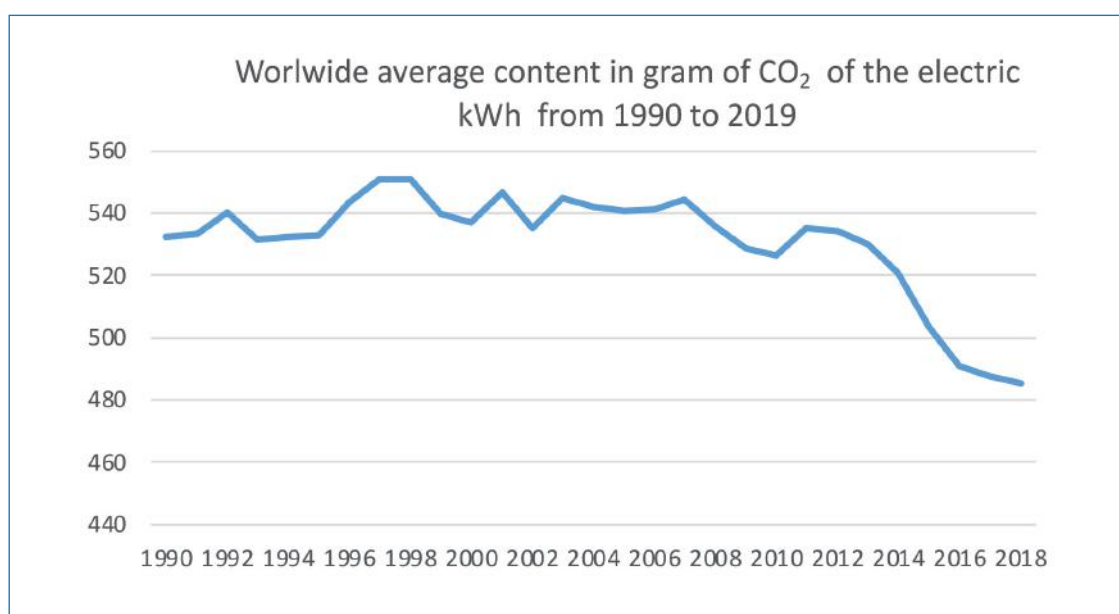
Passing from one of the above options to the next usually entails increasing costs to avoid emissions: the ‘low-hanging fruit’ are often associated with electrification (option 2). They are consistent with the new uses or extensions of uses of electricity, while at the same time advancing the decarbonisation of electricity (which is not the subject of this report).

Even if the energy efficiency of equipment and systems improves, the increasing level of electrification of a growing number of activities, the improvement of the quality of life in poorer countries and regions, and further demographic growth in some parts of the world will generate an increased need for the production of electricity. Such production thus needs to be increasingly decarbonised to sustain the emissions reduction.

For these reasons, the IEA and most other international and national institutions increasingly foresee and promote a higher level of electrification in energy systems and, at the same time, an increase in electricity consumption<sup>6</sup>: at the global scale, the share of electricity in final energy consumption could increase from 19.3% in 2020 to 50% in 2050. As a result, electricity consumption would more than double, from 22 300 TWh in 2020 to around 50 000 TWh in 2050.

At the same time, the related CO<sub>2</sub> emissions from electricity production must decrease. Per kilowatt-hour, indeed, this has been achieved since 1990, as shows *Fig. 0.3*<sup>7</sup> below, dropping from 533 gCO<sub>2</sub>/kWh to 485 gCO<sub>2</sub>/kWh. This decrease is, however, counterbalanced by an expansion in consumption, resulting in an increase in the total emissions from electricity production from 1990 to 2019.

The global decarbonisation of electricity must therefore proceed, as rapidly as possible especially through increasing the share of renewable and nuclear energy, as previously seen.



**Fig. 0.3.** Worldwide average CO<sub>2</sub> content of electricity 1990 to 2019 [CO<sub>2</sub>/kWh]

Source: IEA

<https://www.iea.org/data-and-statistics/data-product/emissions-factors-2021>

For the last two options above, technologies are available but still need incentives, such as new regulations imposing higher prices for CO<sub>2</sub> emissions, or new business models to be deployed extensively. The number of demonstration projects, pilot projects, and first industrial projects in different countries is increasing. Some of them are described in the chapters of the report.

<sup>6</sup> The potential level of electrification sector by sector of the european countries has been studied in the eXtremOS project realised by a consortium of academic and industrial german partners: <https://extremos.ffe.de/>

<sup>7</sup> See for reference: <https://www.iea.org/data-and-statistics/data-product/emissions-factors-2021>

### 3. Fifteen general comments

The following general comments apply to most, if not all, of the sectors studied in this report and generally to other sectors it does not cover. Some are more oriented on technical aspects, other more on regulatory or industrial policy choices. These comments are evidence-based, and while some may seem ‘simple’, many obstacles beyond technical aspects are still standing in the way of their implementation.

Unfortunately, it is not very difficult to find examples in many countries of feasible choices or solutions that do not seem to be implemented at a sufficient scale, or at all. There are nevertheless a large number of examples in which best practices and solutions have been properly taken into consideration and implemented. Some are listed below; others can be found in the various chapters and the annex of the report.

#### Low-carbon available technologies

The urgency of climate mitigation implies deploying as soon as practicable the best available and most cost-effective lower-carbon intensive technologies. Fortunately, a number of such technologies are already commercially available and at an affordable cost; moreover, many of them offer co-benefits such as reduced energy bills, improved comfort and health, improved industrial processes and/or increased demand flexibility. This is especially true for the first and second options listed above.

##### *The heat pumps family*

While the use of heat pumps is increasing worldwide, it is worth further promoting this family of technologies as it has an increasing range of applications, from residential and tertiary sectors to many industrial processes. Furthermore, the reuse of waste heat might have more applicability in the future. By “pumping” heat, heat pumps bring heat (or cold) where it is needed while using less electricity than would otherwise be needed to heat (cool) a space or equipment, and this by a factor which may be frequently higher than 3. Heat pumps are a key lever for reducing CO<sub>2</sub> emissions. They are described in the first section of the annex to this chapter.

#### Local adaptation of some technologies

Many existing technologies are available globally, but some have been developed and will be used in highly developed countries, also known as the ‘Global North’. These technologies may require adaptation to different climates and local contexts. In some cases, further developments are needed. In particular, some equipment is climate sensitive. For example, air-air heat pumps and solar water heaters are sensitive to temperature and humidity.

#### Energy efficiency and the rebound effect

Energy efficiency is always useful: technologies that are improving equipment efficiency and system insulation save energy. So does adding a modern command-control into an industrial process or into a heating system at a home: replacing a thermomechanical thermostat with an electronic one reduces the energy consumption by 5% to 10%, as it avoids overheating. Command-control with a learning capacity, using AI, may be increasingly useful.

Frequently, these improvements rapidly pay for themselves and become profitable if the outdated equipment is replaced at the right time with a more efficient one, at the end of its life, for example.

Increased energy efficiency may improve the quality of life in a home, especially for the less affluent for whom energy costs tend to be a large portion of their disposable income. However, improvements in energy efficiency may often be subject to the well-known rebound effect (also known as the ‘Jevons paradox’) when consumption is no longer limited by cost. Higher efficiency may indeed lead to an increased, often wasteful, use of resources as their prices decrease and their availability increase. This trend may limit or cancel the expected reduction in energy consumption and emissions. This is often the case for heating at home: people now tend to maintain their homes at higher temperature than before the improvement of the equipment, to feel more comfortable. Other well-documented indirect rebound effects occur when the cost reduction due to an increase in efficiency

lets the consumer spend more energy on other activities.

### Life Cycle Assessment

Life Cycle Assessment (LCA, also known as Life Cycle Analysis) is useful for assessing not only the impact of a process, equipment or system, but also its proposed replacement by another process, equipment or system to produce a more effective and sustainable decrease in GHG emissions. The goal is not necessarily to obtain a highly precise LCA figure but to evaluate the externalities of an initial choice or of a potential replacement that could be useful for reducing GHG emissions. The different types of LCAs are presented in the third section of the annex of this chapter.

### Recycling, circular economy and the reduction of GHG emissions

The development of long-life products, recycling and a circular economy generally leads to reductions in GHG emission, pollution, and use of materials. Recycling requires energy (both to recover what is to be recycled and for recycling itself). For some important materials such as steel and aluminium, the emissions produced by recycling are indeed lower than for the initial production, but this is not always the case. Recycling is not necessarily easy to organise, implement and finance, but it is often desirable.

#### *Example: the recycling of steel*

The recycling of steel generally requires less than one fourth of the energy needed for its production from iron ore; furthermore, recycling scrap uses mainly electricity, thus allowing less CO<sub>2</sub> emissions, if the electricity is produced from lower carbon intensive sources. This approach may be especially useful during the next 30 years or more until hydrogen reduction processes are available and applied on a large commercial scale. With increased recycling, the average energy use for 1 tonne of steel could be reduced by 30% to 40% and the average CO<sub>2</sub> emissions per tonne by about 70% (see *Chapter 6. on the Iron and Steel industry: Fig. 6.10. in Section 2.4., Footnote 15. in Section 2.3., Table 6.1. in Section 2.5.2.*).

### Importance of holistic approaches

Holistic approaches are essential for an effective and affordable transition to a lower carbon intensive economy to be achieved because there are many interconnections between sectors, political choices, regulations and industrial developments or decline. This implies that public and local services should work across and between administrations and governmental agencies without forgetting interaction with industry. Collaborations are also needed at the national and international levels. It is important to specify the varying timing of the different transformations: roadmaps or planning based on solid and transparent simulations are the basic tools needed to gain acceptance and support. Many IPCC reports are examples of such a holistic approach.

### Different impacts of ICT

The increasingly ubiquitous digitalisation of our world and daily lives is transforming the world's value chains, offering numerous possibilities for measures, analysis, optimisation, etc., which may contribute to reducing energy consumption and GHG emissions. On the other hand, information and communications technology (ICT) induces GHG emissions as it requires important amounts of energy in operation, principally in the form of electricity, and also other energy vectors in manufacturing. This report is principally devoted to the energy use on the operation side (see *Chapter 7.*).

### Stability and predictability of regulatory changes

Public policies (regulations, mandates, incentives, etc.) usually concern many stakeholders (from citizens to industrial companies but also cities and national governments). To be accepted and sustainable in many countries, these policies need to be transparent, adequate and, if possible, stable. As far as possible, the evolutions of these policies and their rationale should be announced well in advance so that key stakeholders to adapt and to gain confidence and create acceptance of the general public. Setting a clear path for coming policy

changes, and making it known to the stakeholders, will help predicting with some certainty their evolution and acceptance.

### Importance of metrics and data sources

It is necessary to choose the right metrics and reliable and reproducible data when selecting or defining objectives and monitoring the implementation of any GHG reduction programme. We recommend using metrics for emissions and final consumption rather than primary consumption, because reducing primary energy consumption and reducing emissions are not necessarily synonymous: replacing coal or gas with electricity may increase primary energy consumption and yet decrease CO<sub>2</sub> emissions: see for example *Chapter 6*. on the steel industry, and below.

#### *Low primary energy and low CO<sub>2</sub> emissions are not necessarily synonymous*

Let's suppose a country has the following electricity mix<sup>8</sup>:

50% renewables (hydro, solar, wind), 25% nuclear, 25% gas (with 50% efficiency, thus 400 gCO<sub>2</sub>/kWh)

In that case, following the IAE coefficients (3 for nuclear), the ratio primary energy to final energy is given by  $E_p / E_f = [(50\% \times 1) + (25\% \times 3) + (25\% / 0,5)] / 100\% = 1.75$

The CO<sub>2</sub> content of electricity is:  $25\% \times 400 = 100 \text{ gCO}_2/\text{kWh}$ .

Considering two identical houses with a yearly heating need of 4 MWh.

- One house is heated by a gas furnace of efficiency 100% (to simplify).  
*Its primary energy consumption is thus 4 MWh and its emissions are 400 kgCO<sub>2</sub>.*
- The other house is heated by a heat pump with a Seasonal Coefficient of Performance (SCOP) of 3.  
*Its primary energy consumption is 7 MWh ( $4 \times 1.75$ ) and its emissions are  $(4 \text{ MWh}/3) \times 100 \text{ kg/MWh} = 133 \text{ kgCO}_2$ .*

With this electricity mix, it is thus better to take directly CO<sub>2</sub> emissions as indicators than to take the primary energy.

### Impact of size on the transition in capital-intensive sectors

The urgent need to reduce GHG emissions and the externalities of the required changes call for an exploration of scale issues, such as the size of the facilities under consideration.

In most capital-intensive industries, generally heavy industries, facilities have become increasingly bigger due to the benefits of economy-of-scale, and more and more have been operating continuously with fewer shut-downs for repair and maintenance. These large complex facilities have been highly optimised to increase in efficiency and consequently profitability, which makes it all the more complicated to modify them. Many of these existing facilities have long remaining life spans, which decreases incentives for replacing them.

As a result, changing today's large facilities, in order to reduce GHG emissions or integrate with other processes, requires comprehensive planning, clear regulatory environments, and large investments: such changes indeed typically take several years to implement. If their production needs to be curtailed to modify the process, the whole local industrial ecosystem might suffer from it and so might numerous customers.

<sup>8</sup> Producing 1 kWh by combustion of gas produces some 200 g of CO<sub>2</sub>. We take into account the standard ratio from the International Energy Agency of primary energy over final energy for nuclear electricity (coefficient 3).

## Benchmarking

Benchmarking, particularly in industry, is a way to promote dynamics for emission reductions: comparing for example how much kgCO<sub>2</sub>/tonne of production different companies from the same sector emit may help these companies and public authorities pursue emission reduction goals.

### *Japanese benchmarking system for industries*

To improve energy efficiency in industrial sectors, Japan introduced a benchmark system in 2009 combining regulation and incentives. 70% of industrial and commercial sectors are currently covered by this system. In each area, a simple and easy-to-understand measurable benchmark performance indicator is defined; a benchmark target level is then set, representing the best available technology, already achieved by 10% to 20% of top performers from that sector and also high-ranking in the international EU Emissions Trading System (EU ETS) for the year 2030. This target may be revised if a majority of companies have achieved it. The benchmarking system includes: (a) Inspections by the Ministry of Economy, Trade and Industry (METI) of businesses whose efforts in energy efficiency are unsatisfactory; and (b) Energy-efficiency subsidies when a benchmark target is achieved.

With this system, the government may compare energy intensities among companies and discern each industry's energy efficiency potential; conversely, each of the industries and companies can recognise its own energy efficiency potential. The whole process is based on a strong existing relationship between METI and Japanese industrial associations.

## Synergies between uses and resiliency

Developing synergies can be an effective way to reduce energy needs and associated emissions. For example, waste heat from data centres may provide heat to office buildings or swimming pools, and waste heat from industrial sites may supply heat networks.

This coupling between systems is beneficial in normal operations and should be developed where possible. However, to avoid unacceptable disruptions or at least limit them, in case one of the systems fails, the resiliency of each system should be studied and adapted if necessary; if necessary, adapted backup systems may indeed have to be installed. More generally, resiliency at the strategic level as well as for everyday operation will be studied before the transformations for GHG emissions reduction are chosen.

## RD&D

RD&D efforts are essential in all areas to provide new opportunities for the needed energy transition as well as to mitigate and adapt to the currently occurring climate change and all other resulting global changes.

RD&D efforts are not only required in the areas of technology, engineering, systems modelling and simulation but also in the complementary areas of humanities and social sciences - in particular but not only how technologies are perceived with their known and unknown benefits, advantages and disadvantages, and consequences. These key issues, however, mostly lie beyond the scope of this report.

## Skills and competencies

All the members of the Committee and its Working Groups are convinced that training / professional development is a key issue: many jobs will disappear in the transition driven by GHG reductions while, others will change, and new ones are likely to appear. Therefore, some skills will no longer be needed while others will have to change/adapt, and new ones will be needed.

This issue concerns all educational systems in the world, starting from elementary school. It also involves updating skills and developing new ones during one's working life, in particular in engineering and technologies. This is a concern for large and small companies, and for society as a whole. A large effort is needed to rethink teachers' training and provide more opportunities for lifelong learning both in educational institutions and in the internal training organisations of industrial and service companies.

## Leadership, collaboration, networking and social issues

The urgency of the transformation that must be accomplished, the necessity for choices and agendas to be consistent with one another in different sectors, and the need for arbitration between multiple conflicting interests, call for effective leadership is and very high level in the different sectors. Collaboration and networking contribute to the development of confidence and sharing of best practices. Such is the role, for example, of city networks. Effective cooperation also lies in the different networks that link Academies in the world with one another, as CAETS does. Social issues are ubiquitous and essential but beyond the scope of this report, as already mentioned.

## Annex

### Three transversal levers for the transitions: heat pumps, hydrogen, LCA

Three different and important elements or tools may be applied to almost all sectors and are described below.

- Heat pumps form a family of systems mobilising local renewable heat from the air, the water or the ground. They are not yet as widely deployed as they could be.
- Hydrogen as an energy vector: the use of hydrogen and hydrogen-based molecules (synthetic fuels) may be regarded as a stimulating way to decarbonise several industrial processes that cannot be directly electrified.
- Life Cycle Assessment methods (LCA) help understand the global impact of processes and changes to such processes.

This annex briefly describes these three technologies, which are technical levers for the transition.

#### 1. Heat pumps: a key technology family for the transition

In nature, heat flows from a warm body to a colder one. Heat pumps work the other way around: they transfer residual heat from cold places (making them even colder) to warm or warmer ones. Refrigerators and air-conditioning systems, well-known to many, are examples of common heat pumps.

- The refrigerator ‘pumps’ heat from the inside to keep it cool or cool it even more and expels it outside, generally in the kitchen, where the temperature is about 20 °C or more. It is thus at the same time slightly heating its environment.
- The air-conditioning system extracts heat from the inside of a house or any built structure, thus transferring it to the warmer area outside. At the same time it is thus also slightly heating the outside air.

Heat pumps, which are the reverse of air conditioning, are increasingly used for heating in northern countries in winter and reduce CO<sub>2</sub> emissions and lower energy consumption: in such a case, the heat pump extracts residual heat from the outside, where it is cold, transferring it to the inside, where it is already warmer. This application of heat pumps for heating is generally simply referred to as ‘heat pump’.

### Heat pumps demystified

The heat pump operating principle is based on the three main ideas that rule the phase shift of a heat transfer fluid from liquid to gas and conversely.

1. To vaporise a liquid into gas, heat must be transferred to the liquid (as for example when water is boiled). Conversely, liquefying a gas releases heat.
2. The higher the pressure, the more heat is needed to vaporise a liquid since the generated gas has to overcome the external pressure. In other words, the temperature needed for the vaporisation of the liquid increases with the external pressure. Likewise, the liquefaction temperature of a gas thus increases with the pressure.
3. When you rapidly compress a gas, its temperature increases (as does for example the air in a bicycle pump).

The principle of the heat pump is to find a fluid that will, under certain pressure, vaporise at the outside temperature, and under higher pressure liquefy at the inside temperature, thus releasing heat inside: this requires low outside pressure (for vaporisation to capture heat) and high inside pressure (for liquefaction to release heat).

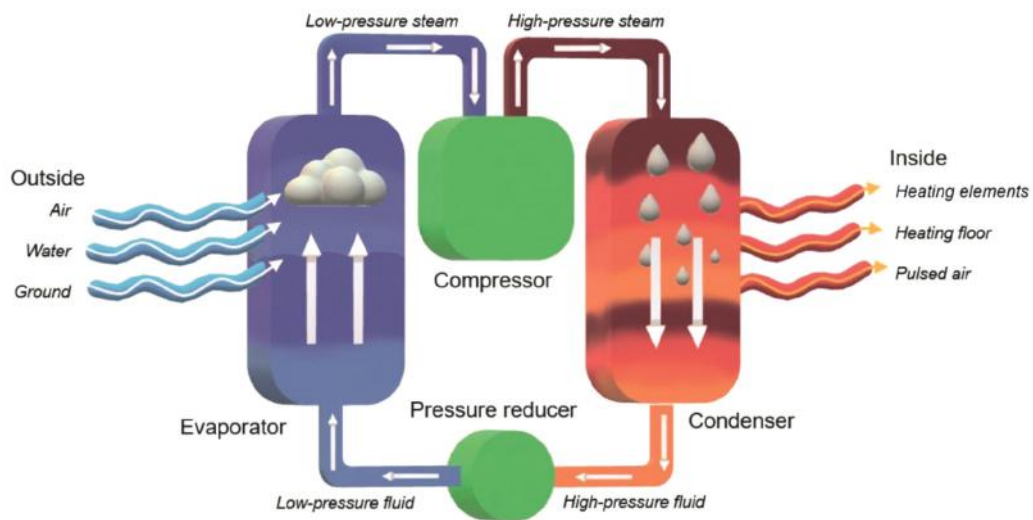


Fig. 0.4. Heat pump operating principle (© Püttgen-Bamberger)

A heat pump is thus composed of *a fluid in a closed loop* and:

- outside the home, a *low-pressure evaporator*, where the fluid arrives liquid and adsorbs the residual heat to vaporise;
- inside the home, a *compressor* ensuring the circulation and compression of the gas, where the temperature increases with increasing pressure;
- inside the home a *condenser*, where the gas releases heat;
- a *pressure reducer*, where the cooled gas returns to liquid before being pumped again to the outside evaporator to be vaporised again.

The key advantage of a heat pump is that it provides more heat than the energy consumed by the compressor. The ratio referred to as the Coefficient of Performance (COP) is regularly higher than 3. A COP equal to 3 means that the heat pump produces 3 kWh when only 1 kWh of electricity is consumed.

Gaining 2 kWh from the outside is generally considered as renewable energy even if a (very) little decrease of the outside temperature results from it. The COP depends on the inside and the outside temperature. It is higher when the temperature difference is lower. In addition, when the outside temperature decreases,

it becomes more difficult to recover heat and the COP decreases, which is clearly contrary to the desired output. This often imposes a limit to the temperature range in which heat pumps can work efficiently. This range is usually narrower than with direct heating.

Heat pumps are a broad family. They are characterised by the mediums from which the heat is extracted and to which it is provided. Heat pumps are referred to as air-air, air-water, etc., the first word designating the heat source, the second the medium where the heat is released. Some heat pumps are reversible and may be heating or cooling. Generally, one is more efficient than the other.

The heat transfer fluid, also known as the working fluid or coolant, is another important characteristic. Coolants themselves may be greenhouse gases which is a problem in the case of leakage. In an increasing number of countries, regulations impose coolants with low impact on climate change.

Heat pump ratings can range from a few kW to several MW. Their performance has been improving over the last 50 years, in particular for larger ranges of operation with higher COPs. They may be used for example:

- to heat or refresh apartments, houses, offices, and industrial processes
- to reuse waste heat from industrial processes by modifying their temperature
- to modify temperature from geothermal sources.

This short list suggests numerous potential applications for decarbonisation and reduction of energy consumption: comparing with a classical heating system using resistive heating, emission and consumption are divided by the COP value. If the COP is 3, then, compared to an efficient gas heating system emitting 200 gCO<sub>2</sub>/kWh, the emissions from the heat pump system are lower, provided the electricity mix contains less than 600 gCO<sub>2</sub>/kWh. This is the case in many regions since the average CO<sub>2</sub> content of 1 kWh in the world in 2019 was 485 g.

## 2. Hydrogen: a key vector to complete electricity

Hydrogen is a key chemical element in many industries such as petroleum refining and chemicals production. Currently, more than 95% of it is produced from fossil fuels, natural gas, petroleum and coal – by far the cheapest way to obtain it as will be detailed below. Hydrogen can yet also be produced from a wide range of energy sources and technologies, as highlighted in *Table 0.1*. The most commonly used colours to depict hydrogen are green, blue and gray, and also brown as in *Table 0.1*. below.

Hydrogen color spectrum	
<b>Green:</b> hydrogen produced by electrolysis of water, using electricity from renewable sources like hydropower, wind, and solar. Zero carbon emissions are produced	<b>Turquoise:</b> hydrogen produced by the thermal splitting of methane. Instead of CO <sub>2</sub> , solid carbon is produced
<b>Pink/purple/red:</b> Hydrogen produced by electrolysis using nuclear power	<b>Black/gray:</b> hydrogen extracted from natural gas using steam-methane reforming
<b>Yellow:</b> hydrogen produced by electrolysis using grid electricity	<b>Blue:</b> gray or brown hydrogen with its CO <sub>2</sub> sequestered or repurposed
<b>White:</b> hydrogen produced as a byproduct of industrial processes (i.e. fracking)	<b>Brown:</b> hydrogen extracted from fossil fuels, usually coal, using gasification

Source: North American Council for Freight Efficiency. 2020.

Table 0.1. Hydrogen colour spectrum

Source: <https://nacfe.org/wp-content/uploads/2020/12/Hydrogen-Color-Spectrum-HiRes-2.png>

The cleanest versions, as it were, are ‘green’ and purple’ hydrogen. Both are generated in relatively small quantities today by electrolysis, using electricity respectively from renewable energy sources and from nuclear energy.

The most common type of hydrogen is known as ‘gray’ hydrogen as its production releases significant amounts of greenhouse gases in the atmosphere. A cleaner proposed version is ‘blue’ hydrogen, which would still be produced from fossil sources but for which CO<sub>2</sub> emissions will be captured and geologically sequestered or reused, instead of being released into the atmosphere.

Gray hydrogen is mainly produced by the chemical conversion of methane at high temperatures. In some countries, significant amounts of hydrogen are produced from coal. The most common method of production is *Steam Methane Reforming* (SMR), where pure steam is used as the oxidant. Through endothermic (absorbing heat) reactions at 700-900 °C, methane and water are converted into hydrogen, carbon monoxide and carbon

dioxide ('synthesis gas').

Gray hydrogen can also be produced by one of the processes below.

- By the *Partial Oxidation* (POX) of methane or heavy hydrocarbons. The process takes place under high pressure and at high temperatures (up to 1 400 °C).
- By *Auto-Thermal Reforming* (ATR), a combination of steam reforming and partial oxidation. The advantage of the auto-thermal reaction is that it is not dependent on external heat supply. However, ATR benefits are offset by increased investment and operating costs for the air separation unit and a more complicated flue gas purification process.

Table 0.2. below presents the CO<sub>2</sub> emissions associated with the production of g hydrogen in the best-case scenario (D. Jakobsen & V. Åtland, 2016).

Process	CO <sub>2</sub> Emission (tonne CO <sub>2</sub> / tonne H <sub>2</sub> )
SMR	8.5
POX	8.6
ATR	8.2

Table 0.2. CO<sub>2</sub> emission from H<sub>2</sub> production with natural gas for SMR, POX and ATR

To address the high CO<sub>2</sub> emissions of hydrogen plants, carbon capture, utilisation, and storage (CCUS) has been proposed. Different methods are possible, including an up to 90% reduction for the ATR plant. CCUS, however, increases natural gas consumption and plant operating costs and requires significant capital investment, which translates into higher costs for the production of hydrogen.

Adding CCUS to SMR plants results, on average, in increases of 50% for CAPEX and 10%-20% for energy, with the exact amounts depending on the design. It also leads on average to a doubling of OPEX as a result of CO<sub>2</sub> transport and storage costs. CCUS cost indications are given in the literature.

In the case of natural gas, costs from SMR with CCUS are in the range of USD 1.4–2.6 /kgH<sub>2</sub>, compared to USD 1.0– 1.9/kgH<sub>2</sub> without CCUS (IEA, 2019), (IRENA, 2019). For more information on the current development of CCUS, which is beyond the scope of this short note, the reader may visit the IEA's website or the global CCS Institute Website (<https://www.globalccsinstitute.com>).

Water electrolysis is an electrochemical process that breaks down water into hydrogen and oxygen gases under the influence of a direct electric current. A product allowing the current to pass through the water, the electrolyte, has to be added. The oldest electrolysis technology, alkaline electrolysis, is mature. Two other types are differentiated by the electrolyte material and operating temperature. The main technical and economic characteristics of the three types of electrolysis and their acronyms are summarised Table 0.3..

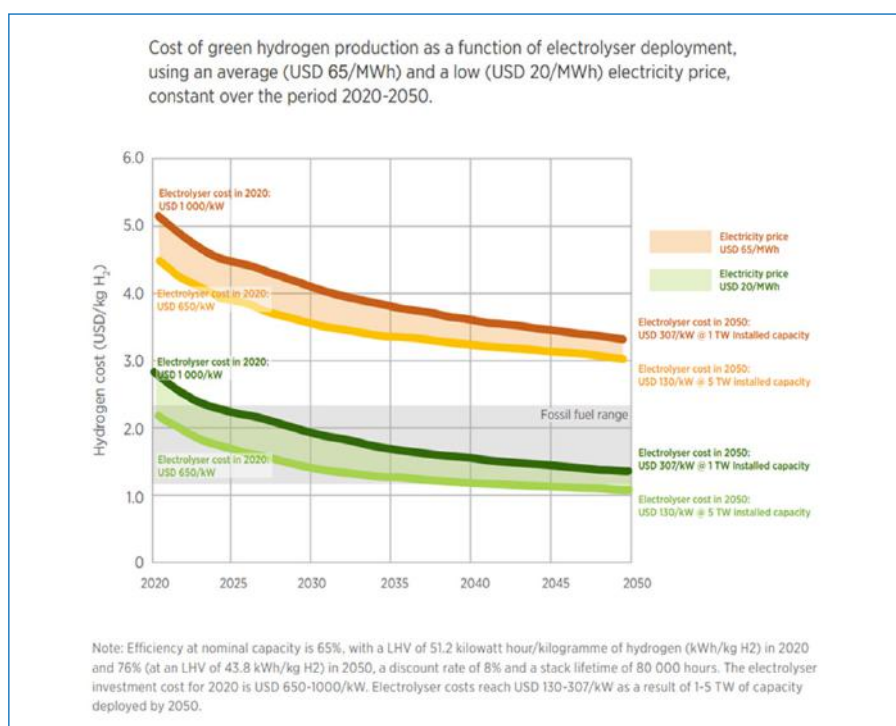
The efficiency of the electrolysis process is defined as ratio of the Higher Heating Value of hydrogen (HHV) to the input electricity used by electrolysis per kilogram of hydrogen produced (Detlef Stolten, 2010).

	Alkaline electrolysis cells (AEC)	Proton exchange membrane electrolysis cell (PEMC)	Solid oxide electrolysis cells (SOEC)
<b>Electrolyte</b>	KOH/NaOH (liquid)	Polymer (solid)	Ceramic (solid)
<b>Operating Pressure (bar)</b>	2-10	15-30	<30
<b>Operating Temperature (°C)</b>	60-90 (up to 200)	50-90	500-1000
<b>Stack Lifetime (h)</b>	<90,000	<40,000	<40,000
<b>System Lifetime (year)</b>	20-30	10-20	-
<b>Efficiency (HHV)</b>	62-82%	67-84%	~90%
<b>Cold Startup (min)</b>	>15	<10	>60
<b>Annual Degradation (%)</b>	2-4	2-4	17
<b>Cost at 2019 (US\$/kW)</b>	500–1400	800–1800	> 2800
<b>Target Cost by 2050 (\$/kW)</b>	~574	~700	~200

**Table 0.3.** Source: Electrolyser key features (Kai Zeng, 2010) (Mergel, 2013) (Bertuccioli, 2014) (IEA, 2016) (Uosaki, 2017) (M. Carmoa, 2013), (IEA, 2019), (Nel, 2019) [https://transitionenergetique.gouv.qc.ca/fileadmin/medias/pdf/expertises/Etude\\_hydrogene\\_Volet\\_B.pdf](https://transitionenergetique.gouv.qc.ca/fileadmin/medias/pdf/expertises/Etude_hydrogene_Volet_B.pdf)

As mentioned earlier, at present, the production cost of ‘green’ hydrogen is significantly higher than that of gray hydrogen – up to 5 times or more. The magnitude of the cost differential depends on the cost of electricity at the point of production and the electrolysis technology used. The cost of electrolyzers per kilo of produced hydrogen is decreasing, in particular through their increasing capacity: a 20 MW PEMC electrolyser producing 8.2 tonnes hydrogen a day is operated by Air Liquide since 2021.

Production parity cost between gray, blue and green hydrogen could be met in the present decade. The following figure from IRENA gives some projections concerning green hydrogen costs (see *Fig. 0.5.*).



**Fig. 0.5.** Green hydrogen production costs projected by IRENA.

[https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA\\_Green\\_hydrogen\\_cost\\_2020.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf)

To complete this brief description on hydrogen production and cost, it is useful to compare the energy efficiency of electrolysis as a means to produce hydrogen with that of processes synthetically producing fuels,

respectively methane, diesel, methanol and ammonia, and combining electrolysis and supplementary chemical reactions (DNV 2019, Energy Transition Outlook (2020)). Such is the object of *Table 0.4.* below.

	Hydrogen	Synthetic methane (LNG)	Synthetic diesel	Synthetic methanol	Ammonia
Energy efficiency (%)					
Electrolysis	71	71	71	71	71
Power-to-gas process	-	75	-	-	87
Liquefaction	83	96	-	-	-
Power-to-liquid process	-	-	75	75	-
Overall efficiency	59	51	53	53	62

*Table 0.4.* Compared energy efficiency in per cent of different synthetically produced fuels

### 3. Life Cycle Assessment (LCA): a key methodology to analyse emissions

Life cycle assessment, or Life Cycle Analysis, both referred to as LCA, is an established method to model and quantify multiple input and output impacts on processes, products and services. The proper use of Life Cycle Assessments helps understand the effects of any change in a process, product, or technology. For example, it may be useful to assess whether any change to a process, such as trying to reduce its carbon intensity or the resulting GHG emissions, is effective and what its side effects may be. Indeed, well-intentioned actions to reduce the GHG emissions of a process or a product may often inadvertently produce the opposite effects.

LCAs are complex and are not perfect, and in many cases lead to different results. It is therefore critical for LCAs to be conducted using fully transparent assumptions and data sets, stating the accuracy of the inputs and estimating variabilities and uncertainties.

LCA is broadly defined by the ISO 14040:2006 standards<sup>9</sup> as a “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.” ISO 14040, however, does not provide specific recommendations on methods or tools for conducting an LCA since there are a wide variety of methods for it.

The 4 basic phases of an LCA are described below.

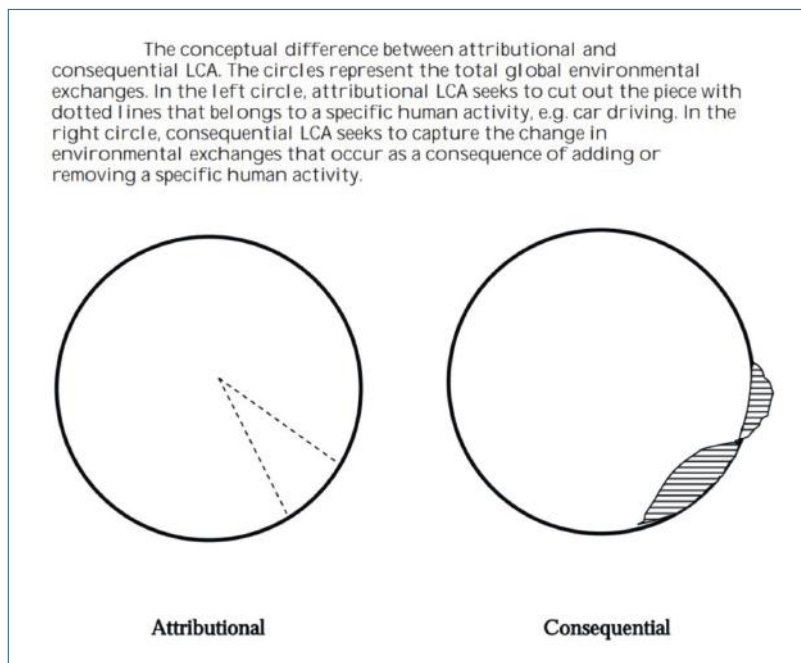
1. The first phase of a typical LCA according to ISO 14040 is the goal and scope definition phase, which lays out the basis for the LCA. In this phase, the modeller specifies the goal for conducting the analysis and the intended use. Typical goals could be: to quantify GHG emissions for different product or process options; to guide R&D; or to define regulatory regimes.
2. Detailed life-cycle inventory (LCI) analysis forms the second phase of an LCA. This may include overall material and energy balances, and a compilation of all relevant and available data throughout a well-defined LCA system boundary.
3. LCA impact assessment (LCIA) is the third phase. Data gathered in the second phase is used to calculate impact results for the chosen parameters, for example, tonnes of CO<sub>2</sub> emitted per unit of product or process. However, much broader desired output parameters may and should be used, such as societal, health, climate, and various other environmental effects. Life-Cycle GHG emissions may be calculated for any pollutant, or as the sum of equivalents of GHG compounds such as water vapour, CO<sub>2</sub>, methane, N<sub>2</sub>O, etc. In many studies, these are combined and reported as global warming potential (GWP) in the form of CO<sub>2</sub>-equivalents (CO<sub>2</sub>e).
4. The fourth usual phase of an LCA is the interpretation phase. Results are then used for reporting, further analysis, or guidance for formulating regulations.

<sup>9</sup> <https://www.iso.org/standard/37456.html>

The LCA process tends to be iterative, as the initial results often highlight uncertainties and the need for additional data or improved modelling tools.

The main LCA types are Attributional, Consequential and Societal, but hybrids or combinations are numerous and common.

Attributional and Consequential LCAs are typically quite different from one another in their formulation, usage and results. Fig. 0.6. below sketches their conceptual difference.



**Fig. 0.6.** The conceptual difference between Attributional and consequential LCAs (from Weidema BP. Market Information in Life Cycle Assessment. Environmental Project no. 863. Copenhagen: Danish Environmental Protection Agency; 2003. 147p. <https://www2.mst.dk/Udgiv/publications/2003/87-7972-991-6/pdf/87-7972-992-4.pdf>)

A description of these differences may also be found in *Attributional vs. Consequential LCA Methodology Overview, Review and Recommendations with focus on Well-to-Tank and Well-to-Wheel Assessments*, a study commissioned by EUCAR to IFP Energies Nouvelles and Spheramodells<sup>10</sup>.

Regulators, indeed, use LCAs and, in doing so, aim at being comprehensive, using for example the ‘well-to-wheels’ approach. However, they do not capture all the rebound effects, unknowns, uncertainties or unintended consequences. Consequential LCA, also known as the CLCA model, is thus increasingly used to try to also take into account some of these indirect and follow-up effects. Still, this model is not really adapted for long-term prediction.

The IPCC uses the Integrated Assessment Model (IAM), or a version of LCA known as Societal-LCA, or S-LCA, which focuses on the demand side, impacts on societies and economies and climate change, and hence provides an insight into how real sustained reductions in energy use and GHG emissions may be achieved.

<sup>10</sup> <https://www.eucar.be/wp-content/uploads/2020/08/20200820-EUCAR-Attributional-vs-Consequential-updated-2.pdf>

---

# CHAPTER 1. FOOD AND AGRICULTURE SYSTEM

## Members of the Working Group

**Adesina Adesoji**, Nigeria

**Caron Patrick**, France (Co-chair)

**Finch Nigel**, United Kingdom

**Hefft Daniel**, United Kingdom

**Pätzay György**, Hungary

**Reinders Felix**, South Africa

**Scott Norman**, United States of America (Co-chair)

The authors express their gratitude to Véronique Bellon-Maurel (INRAE, France) and Stéphane Guilbert (Institut Agro, France).

## Table of Contents

---

<b>Executive Summary</b> .....	34
<b>1. Introduction</b> .....	35
<b>2. Complex interactions between agriculture, food, water, environment and energy</b> .....	37
2.1. The Food and Agricultural System: a definition and challenges for the future? .....	41
2.2. Sustainable Development Goals and the Food and Agriculture System .....	41
2.3. Energy sources ‘fuelling’ the current FAS .....	43
<b>3. Technologies and their potential for decarbonisation</b> .....	46
3.1. Reducing emissions and shifting diets through technology .....	46
3.2. Reducing food loss and waste .....	47
3.3. Valuing new food resources through technology .....	48
3.3.1. Plant-based alternative food .....	49
3.3.2. Cell-cultured food .....	50
3.3.3. 3D-printed food .....	50
3.3.4. Advanced Greenhouses and Vertical Farms .....	51
3.4. Improving food supply through technology .....	52
3.4.1. Regenerative agriculture / agroecology / organic agriculture .....	52
3.4.2. Nitrogen-use efficiency / optimal nitrogen management .....	54
3.4.3. Agroforestry .....	55
3.4.4. Food manufacturing/processing .....	56
3.4.5. Food storage .....	57
3.5. Technology for resource optimisation .....	57
3.5.1. Circular food systems .....	57
3.5.2. Recirculating aquaculture systems .....	58
3.5.3. Integrating Food, Energy and Water Systems (FEWS) .....	59
3.5.4. Improving energy consumption through technology .....	60
3.5.4.1. Bioenergy .....	61
3.5.4.2. Biofuels .....	62
3.5.4.3. Biochar .....	65
3.5.4.4. Solar energy and the co-location opportunity .....	67
3.5.4.5. Wind energy and the co-location opportunity .....	68
3.5.4.6. Geothermal systems .....	68
3.5.4.7. Electrification and electricity on the farm .....	69
3.6. Advanced non-specific technology for FAS decarbonisation .....	69
3.6.1. Computing and information science: Digital Agriculture, or ‘Digital Ag’ .....	69
3.6.2. Sensors .....	70
3.6.3. Robotics and automation .....	70
3.6.4. Drones and Unmanned Aerial Vehicles (UAV) .....	71
3.6.5. Biotechnology .....	72
3.6.6. Nanotechnology .....	73
3.6.7. Cross-cutting technology related observations .....	74

<b>4.</b>	<b>Different narratives</b>	<b>75</b>
<b>5.</b>	<b>Key messages and recommendations</b>	<b>76</b>
5.1.	Major transformations	76
5.2.	Decarbonisation and methane reduction	76
5.3.	Disruptive technologies and behaviour	76
5.4.	System of systems	76
5.5.	Advances in science and technology including design and metrics	76
5.6.	Quantitative impact of specific technologies	76
5.7.	Stable Public Policies	77
5.8.	Need for research and extension	77
5.9.	Food supply chain	77
5.10.	Methane reduction	77
5.11.	Energy efficiency and decarbonisation	77
5.12.	Alternative protein foods / Controlled environment agriculture	77
5.13.	Circular economy	77
5.14.	Biomass / Bioenergy	77
5.15.	Biotechnology	77
5.16.	Nanotechnology	78
5.17.	Nitrogen use efficiency	78
5.18.	Regenerative agriculture / Agroecology / Agroforestry	78
5.19.	Digital Agriculture	78
5.20.	Policy framework	78
	<b>List of abbreviations and acronyms</b>	<b>79</b>

## Executive Summary

No area of human activity is more essential to society than a sustainable Food and Agriculture System (FAS). With projections that the global population will grow to as much as 10 billion by 2050, there is increasing concern as to how this system should be transformed to feed the population while contributing to sustainable development. Agricultural productivity has been a consistent and important focus of attention during the 20<sup>th</sup> and 21<sup>st</sup> centuries, with good reason, as it aimed to feed such growing world population. While a driving goal for the FAS remains providing safe and affordable food numerous emerging factors challenge our present and future food and agriculture system.

This chapter addresses the decarbonisation of the Food and Agriculture System by considering the advancement of many scientific and technological developments that may transform the existing one. The global FAS is responsible for about 33% of total anthropogenic emissions according to IPCC (2022)<sup>1</sup> but this percentage can vary somewhat according to other reports and how the FAS is defined. The chapter focuses on: the characterisation of the FAS, from domestication to today's highly complex and adaptive system; both the impact of the FAS on the environment and the effect of the environment on the FAS (climate change); the role of the FAS as an energy supplier as well as an energy consumer; the effects of changing food preferences and dietary changes on emissions and energy; the role of the FAS in meeting Sustainable Development Goals (SDGs); the challenges of socio-technical innovations across global and local levels; and the impact of such specific technologies as renewable energy sources (solar power, wind, geothermal and bioenergy, including biofuels and biochar), digital agriculture, nanotechnology, biotechnology (CRISPR), regenerative agriculture/agroecology, agroforestry, electrification, the circular economy, and synthetic biological food developments.

Technology played a pivotal role in the impressive agricultural transformation that took place in the 20<sup>th</sup> century. And technologies should similarly play an essential role in addressing current and future sustainability challenges that bring together agriculture, food, health, energy, climate, environment, and social justice. While technology should be considered a necessary and useful resource, there is no magic bullet, nor a 'one size fits all' solution. Any technology may offer potential avenues for progress and provide benefits but also bring about drawbacks and contribute to the emergence of new problems. In addition, the profound changes that are required today will depend on a series of many complementary solutions, as no single one might address the breadth and depth of this challenge. These basic assumptions first call for the need to generate appropriate metrics and assessments that account for the capacity of technology to contribute, not only to decarbonisation but also to all the dimensions of sustainability as there might be trade-offs among them. This is challenging: most assessments are context- as well as time-, space-, and scale-specific, accounting for complex and uncertain processes, and require methods and indicators that are not always available. These assumptions also call for context-specific design processes. This is essential to jointly consider technological resources, the innovation process, and the contributions to addressing sustainability concerns.

Agricultural and food systems are quite context-specific. Their transformation relies on locally adapted practice changes that depend on resources and available technology, know-how, risk management, etc., and may involve various stakeholders with divergent vested interests. In addition to the discussions on its impacts, technology implementation may thus face resistance related to values and interests, conflicts of interest, risk management and path dependency that make it very complex to analyse its political economy. Finally, technology may have a controversial dimension and, alongside growing suspicion concerning technology and the spread of fake news, may become a polemical and polarising issue. To address such challenges, the chapter provides a critical review of both the benefits and drawbacks of technology. It identifies four different scenarios taking into consideration the main drivers, and finally presents key messages and recommendations.

<sup>1</sup> IPCC-AR6-WGIII. 2022. Chapter 7. Agriculture, Forestry and Other Land Uses

## 1. Introduction

The purpose of this chapter is to address decarbonisation in the Food and Agriculture System (FAS) by considering the advancement of numerous scientific and technological developments that can transform the existing FAS. It focuses on: the characterisation of the FAS from domestication to today's highly complex and adaptive system; both the impact of the FAS on the environment and the effect of the environment on the FAS (climate change); the role of the FAS as an energy supplier as well as an energy consumer; the effects of changing food preferences and dietary changes on emissions and energy; the role of the FAS in meeting Sustainable Development Goals (SDGs); the challenges of socio-technical innovations across global and local levels; and the impact of such specific technologies as renewable energy sources (solar power, wind, geothermal and bioenergy, including biofuels and biochar), digital architecture, nanotechnology, biotechnology (CRISPR - clustered regularly interspersed short palindromic repeats), regenerative agriculture, electrification, the circular economy, and synthetic biological food developments.

There is no area of human activity more essential to society than a sustainable Food and Agriculture System. With projections that global population will grow to as much as 10 billion by 2050, there is an increasing concern as to how this system should be transformed to feed this population while contributing to sustainable development. Agricultural productivity has been a consistent and important focus of attention during the 20<sup>th</sup> and 21<sup>st</sup> centuries, with good reason, as it aimed to feed a growing world population. While providing safe and affordable food remains a driving force for the FAS, emerging and numerous factors nevertheless challenge our present and future FAS. These include: the impacts of the FAS on the environment (gaseous emissions, climate change and pollution, the degradation of water and biodiversity); distrust in science and technology; increasing urbanisation and changing food preferences; globalisation, droughts, international trade, integrated value chains and price volatility; regulation; energy; the economic viability of rural communities and political stability; the impact of climate change on food production; and, more recently, a recognition of the disruptions that major events, such as a pandemic or a war, can create for the FAS. The following questions are also critical to address: (i) Will the food system reduce or increase hunger and poverty among the poor?, (ii) Will the system enhance or decrease equity and access to food for a healthy and productive global population?

Our existing FAS has evolved since the domestication of plants and animals, traced as far back as approximately 11,000-9,000 BC<sup>2</sup>. From its origin, the FAS has fundamentally been a land-based system with the soil being its one consistent factor. However, emerging subsystems of precision controlled-environment indoor agriculture, as well as alternative protein food systems -- largely established in soilless-based indoor facilities -- are experiencing significant growth.

We thus propose that the evolution of the FAS consists of four relevant periods, which are described below.

- i) **Before domestication.**
- ii) **From domestication to 1960:** a time of agricultural expansion during which production is correlated with land under cultivation.
- iii) **Agricultural industrialisation:** when increase in yield then made it possible to disconnect production and land under cultivation.
- iv) **The expansion of landless agriculture:** its increasing role relies on the emergence of synthetic foods (white and green chemistry) and indoor controlled environment agriculture.

<sup>2</sup> Zeder, M. The origins of agriculture in the near east. 2011. Current Anthropology. <https://www.jstor.org/stable/10.1086/659307>

*Box 1. A farmer recounts how agriculture was transformed in the last 100 years in the UK*

We, in agriculture and food, need to reduce the energy we use and the Greenhouse Gas (GHG) pollution we create daily adding to global warming. In the 1930s ruminating animals were creating methane gas. Steam engines using coal producing CO<sub>2</sub> provided energy to drive corn thrashing machines and some plowing. The remainder of work in the fields was undertaken by horses, pulling all the implements. With men most often walking behind, to plow, cultivate, plant the seeds and harvesting all the crops, with root crops lifted entirely by hand. No artificial energy used. We had no artificial fertilisers, rather using burnt limestone and farmyard manure from food producing animals. No sprays of seed treatments were used. Herdsmen rose by candle, hand milked by lantern light, cooled the milk with stored rainwater, over a surface cooler, filtered into churns. Then delivered by pony and trap to local customers, with a measure from a bucket direct to a customer's jug, the pony moving from house to house. Meat was slaughtered locally, butchered and delivered in the same way. Corn was thrashed and delivered by horse drawn wagons to local steam driven mills producing the flour for baking by local village bakers.

Two World Wars and the subsequent rapid development of the internal combustion engine, plus the need for self-sufficiency in food supply, changed agricultural life completely. Milking machines replaced men; tractors replaced horses. Energy in the form of oil and electricity provided the base to feed a rapidly increasing world population and distribute food around the world – thus unfortunately and sadly contributing to an earth-threatening rise in atmosphere temperature we must counter.

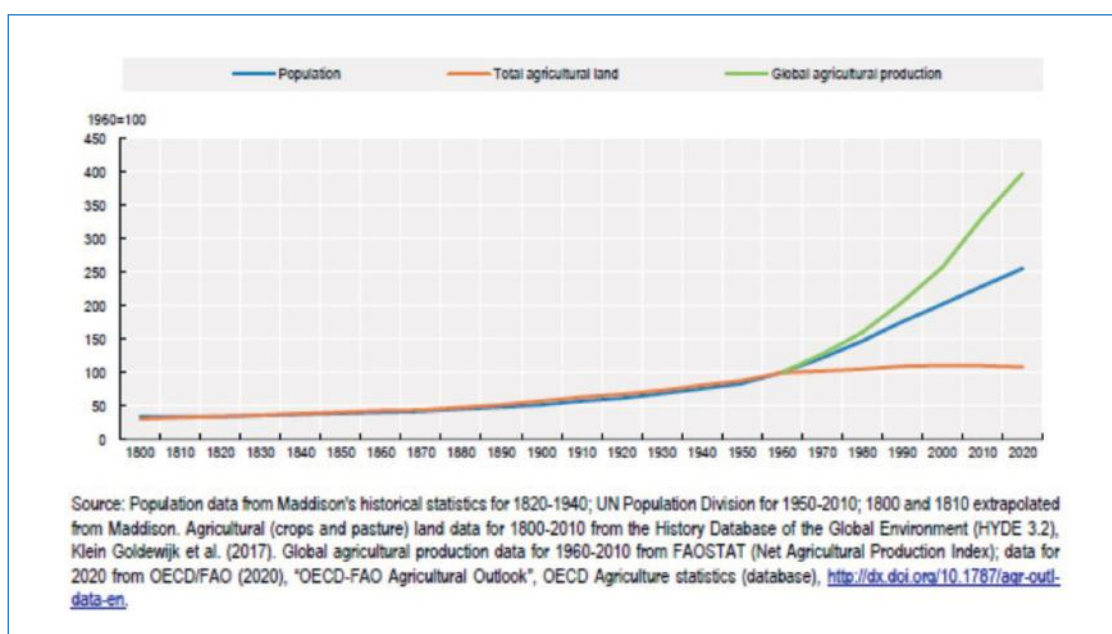
Since the 1960s and, just like other sectors of the economy, food supply underwent an agricultural revolution decoupling land use and production and relying on a carbonisation of food and agriculture systems that is well documented by many scholars. What is known as the modernisation of agriculture (or the 'green revolution' in developing countries), encouraged by active agricultural and price stimulating policies, acknowledged such pillars as:

- the use of fossil energy to support mechanisation and motorisation, resulting in an incredible increase of both labour and land productivity, as well as the extension of cultivated land in particular through its encroachment into the forest as can still today be observed in Amazonia and South-East Asia;
- the mobilisation of chemical inputs in all agricultural practices (fertilisers, herbicides, pesticides, etc.);
- important public and private investment in genetics, genetic improvement, and seed delivery systems;
- the development of long-distance value chains, requiring transport and processing infrastructures and, as a consequence, energy consumption;
- and the significant expansion of irrigated areas based on previous technological assets and public investments in large-scale infrastructure.

Despite population growth, food availability per capita has been continuously growing at the global level because of the modernisation of the agricultural sector and a subsequent increase in production (*Fig. 1.1.*) that has come to exceed the rate of population growth (Paillard et al., 2014)<sup>3</sup>. Yet, while this transformation generated new nutrition concerns, for instance those related to obesity, this has not been sufficient to eradicate hunger, as the number of persons suffering from undernutrition remained stable over the last decades<sup>4</sup>.

<sup>3</sup> Paillard, S., Treyer, S., & Dorin, B. (2014). *Agrimonde—scenarios and challenges for feeding the world in 2050*: Springer Science & Business Media.

<sup>4</sup> HLPE. 2017a. *Nutrition and food systems*. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. Retrieved from <https://www.fao.org/3/i7846e/i7846e.pdf>.



**Fig. 1.1.** Population, food production, and agricultural land use from 1800 to 2020

OECD 2021, "Making Better Policies for Food Systems", OECD Publishing. Paris, Fig 1.7 at page 28. Order License ID 1291258-1

[https://www.oecd-ilibrary.org/agriculture-and-food/making-better-policies-for-food-systems\\_ddfba4de-en](https://www.oecd-ilibrary.org/agriculture-and-food/making-better-policies-for-food-systems_ddfba4de-en)

URL direct access: <https://www.oecd-ilibrary.org/sites/edf73cce-en/index.html?itemId=/content/component/edf73cce-en>

## 2. Complex interactions between agriculture, food, water, environment and energy

The FAS can be characterised as a complex adaptive system that operates across a broad spectrum of economic, biophysical and socio-political contexts<sup>5</sup>. It is at the intersection of some major global issues: food, energy, water, population, land use, and development. Biofuel production and the policies used to support its development can, for instance, be related both positively and negatively with each of the four dimensions of food security – availability, access, utilisation (nutrition) and stability<sup>6</sup>. The impact and feedback links between biofuels and food security require assessments at both global and local levels, recognising ecosystem services and taking into account context specificity.

As already stated, the evolution in the food system has created dramatic consequences and drawbacks on the environment<sup>7,8</sup>. The emergence of these environmental concerns and global actions to prevent catastrophes (climate change, biodiversity loss and land degradation) call for decarbonising the FAS.

- Past transformations of the FAS led to the deterioration of agroecosystems and great losses of specific and genetic biodiversity. In turn, these losses have hampered the FAS in different ways, resulting in the decrease of diversity in food supply and its nutritional value<sup>9, 10, 11</sup>.

<sup>5</sup> National Research Council. 2015. A framework for assessing effects of the food system. The National Academies Press. Washington D.C.

<sup>6</sup> HLPE. 2013. Biofuels and food security. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 2013. <https://www.fao.org/3/i2952e/i2952e.pdf>

<sup>7</sup> Caron, P., Ferrero y de Loma-Orsorio, G., Nabarro, D., Hainzelin, E., Guillou, M., Andersen, I., . . . Verburg, G. (2018). Food systems for sustainable development: proposals for a profound four-part transformation. *Agronomy for Sustainable Development*, 38(4), 41. DOI: 10.1007/s13593-018-0519-1

<sup>8</sup> Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., . . . Murray, C. J. L. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*. DOI: 10.1016/s0140-6736(18)31788-4

<sup>9</sup> HLPE. 2017b. 2nd Note on Critical and Emerging Issues for Food Security and Nutrition. 23. Retrieved from [https://www.fao.org/fileadmin/user\\_upload/hlpe/hlpe\\_documents/Critical-Emerging-Issues-2016/HLPE\\_Note-to-CFS\\_Critical-and-Emerging-Issues-2nd-Edition\\_27-April-2017\\_.pdf](https://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/Critical-Emerging-Issues-2016/HLPE_Note-to-CFS_Critical-and-Emerging-Issues-2nd-Edition_27-April-2017_.pdf)

<sup>10</sup> Hainzelin, E. 2019. Risks of irreversible biodiversity loss. In S. Dury, P. Bendjebbar, E. Hainzelin, T. Giordano & N. Bricas (Eds.), *Food systems at risk. New trends and challenges* (pp. 59-62). Montpellier, France: CIRAD, European Commission, FAO.

<sup>11</sup> FAO. 2019. The state of world's biodiversity for food and agriculture J. Bélanger & D. Pilling (eds.) FAO Commission on Genetic Resources for Food and Agriculture Assessments, (pp. 572). Rome: Food and Agriculture Organization.

- The global food and agriculture system is responsible for up to one third of anthropogenic greenhouse gas (GHG) emissions and is therefore a major driver of climate change<sup>1,12</sup>. This percentage can vary from 25% to 33% according to different reports. According to IPCC (2022)<sup>1</sup>, 24% out of 33% are due to the agricultural and livestock sectors, whereas 9% are generated by Land Use, Land Use Change and Forestry. Emissions from direct on-farm energy use, agricultural practices and fishing are responsible for approximately 1% of global CO<sub>2</sub> emissions, 38% of global methane emissions (CH<sub>4</sub>, essentially related to ruminants' production), and 79% of global N<sub>2</sub>O emissions (essentially related to rice production). Quantitatively, agricultural CH<sub>4</sub> and N<sub>2</sub>O emissions are estimated to average 157 ± 47.1 MtCH<sub>4</sub>/yr and 6.6 ± 4.0 MtN<sub>2</sub>O/yr or 4.2 ± 1.3 and 1.8 ± 1.1 GtCO<sub>2e</sub>/yr respectively between 2010 and 2019<sup>1</sup>.
- Food production, and consequently the livelihoods of billions of people, especially the most vulnerable, including small farmers, is impacted and will be even more in the coming decades by the effects of climate change<sup>13</sup>.
- Although the demographic transition is mainly behind us (apart from Sub-Saharan Africa), consumption trends, including the possible increase of animal source products in the Global South, point to dramatic developments with figures ranging from 50 to 100% increase in production towards 2050<sup>11</sup>.

The FAS system is indeed at the forefront of environmental issues, both as a main contributor to global change, but also as a potential victim or rescuer. It is therefore appropriate to question the capacity of our FAS to feed the global population in a sustainable and resilient manner. Gerten et. al. (2020)<sup>14</sup> conclude that our system, as it currently stands, could at best feed only 4 billion people if all planetary limits were respected. To avoid this predicted failure, four global mitigation 'strategies' are generally proposed: (i) a transition to a healthier diet with less meat; (ii) technological improvements to intensify food production and processing on a sustainable basis; (iii) an important reduction of food loss and waste; and (iv) a political and socioeconomic framework that ensures reduced inequality, lower population growth and strong and coordinated governance of land and oceans.

The challenge is to ensure that new practices and novel technologies, the emergence of increasingly circular and soilless based food systems and the co-existence with more traditional FAS will continue to provide accessible, healthy, tasty, and inexpensive food while reducing its contribution to negative global change and increasing resilience to various risks. The FAS can facilitate mitigation of emissions in a number of different ways. Specifically, it can reduce emissions within the food and agriculture sector, can sequester carbon from the atmosphere, and provide raw materials to enable mitigation within other sectors, including energy, industry, or the built environment.

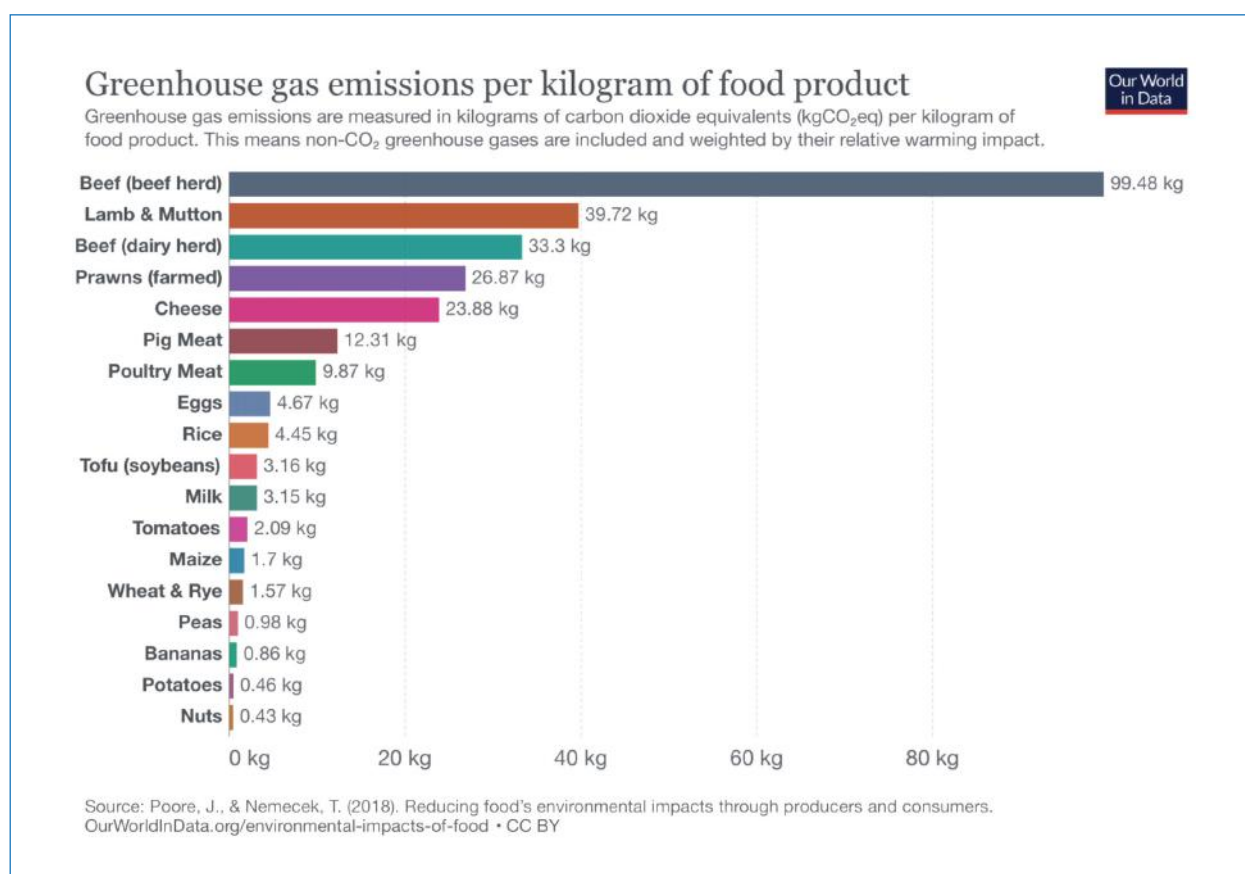
Food is produced and processed by hundreds of millions of farmers and intermediaries, with a significant global impact on the environment. Do differences in environmental impacts depend on specific food products? It is an intriguing and challenging question to answer but a comprehensive study by Poore and Nemecek (2018)<sup>15</sup> has consolidated data on multiple environmental impacts from about 38 000 farms and approximately 1 600 processors, types of packaging and retailers for 40 different agricultural products across the world in a meta-analysis comparing various types of food production systems. *Fig. 1.2.* illustrates differences in GHG emissions/unit of product. Although emissions can be subject to substantial variability along the food chain, it is nevertheless illustrative of the fact that large differences exist between plant sources compared to animal products. Hence the importance of dietary choices.

<sup>12</sup> Xu, X., Sharma, P., Shu, S., Lin, T.-S., Ciais, P., Tubiello, F. N., Jain, A. K. 2021. Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. *Nature Food*, 2(9), 724-732. doi: 10.1038/s43016-021-00358-x

<sup>13</sup> IPCC. 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (Eds.) (pp. 630).

<sup>14</sup> Gerten D., Heck V., Jägermeyr J., Bodirsky B. L., Fetzer I., Jalava M., Kummu M., Lucht W., Rockström J., Schaphoff S., Schellnhuber H. J., 2020. Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nature Sustainability*, Vol. 3, p. 200–208, 2020. <https://doi.org/10.1038/s41893-019-0465-1>

<sup>15</sup> Poore, J. and T. Nemecek. 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360 (6392): 987-992. DOI: 10.1126/science.aag02



**Fig. 1.2.** Greenhouse gas emissions per kg of various food products (Poore and Nemecek, 2018<sup>15</sup>; Ritchie and Roser, 2020)<sup>16</sup>

Ritchie and Roser (2020)<sup>16</sup> have worked with data available from the meta-analysis by Poore and Nemecek (2018)<sup>15</sup> to develop a visualisation of the share of the FAS compared to total emissions and by source across the supply chain (Fig. 1.3.). As previously noted, depending on source and definition, the food system is reported to create about 25% to 33% of anthropogenic GHG emissions<sup>17</sup>. It should be noted that refrigeration and packaging account for about 10% of global FAS emissions or approximately 1/2 of the emissions of the supply chain factors<sup>18</sup>. Also, it should be noted that emissions vary substantially depending on the product.

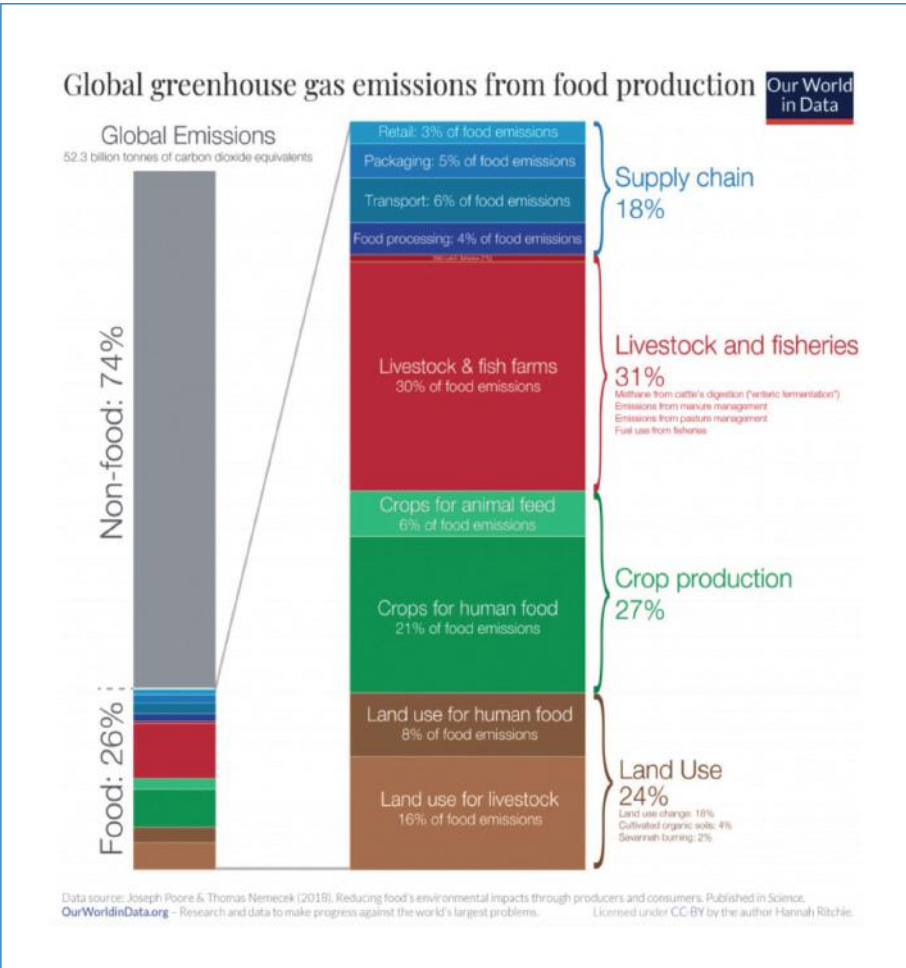
From a study in the EU, in addition to GHG emissions, the FAS impacts the environment in other ways such as toxicity phenomena, eutrophication, acidification, air and water pollution, etc., as shown in Fig. 1.4. which displays the relative impacts of the six stages (activities) for 15 environmental categories. It shows that the agricultural phase (vertical stripes) has the greatest environmental effect in many impact categories because it includes impacts of all agronomic and production activities. The second largest impact activities are process and distribution (logistics), due to the use of thermal and electrical energy. Other lifecycle phases only make minor contributions to the overall impact<sup>19</sup>.

<sup>16</sup> Ritchie, H. and M. Roser. 2020. Environmental Impacts of Food Production. Published online at OurWorldInData.org. Retrieved from: <https://ourworldindata.org/environmental-impacts-of-food>

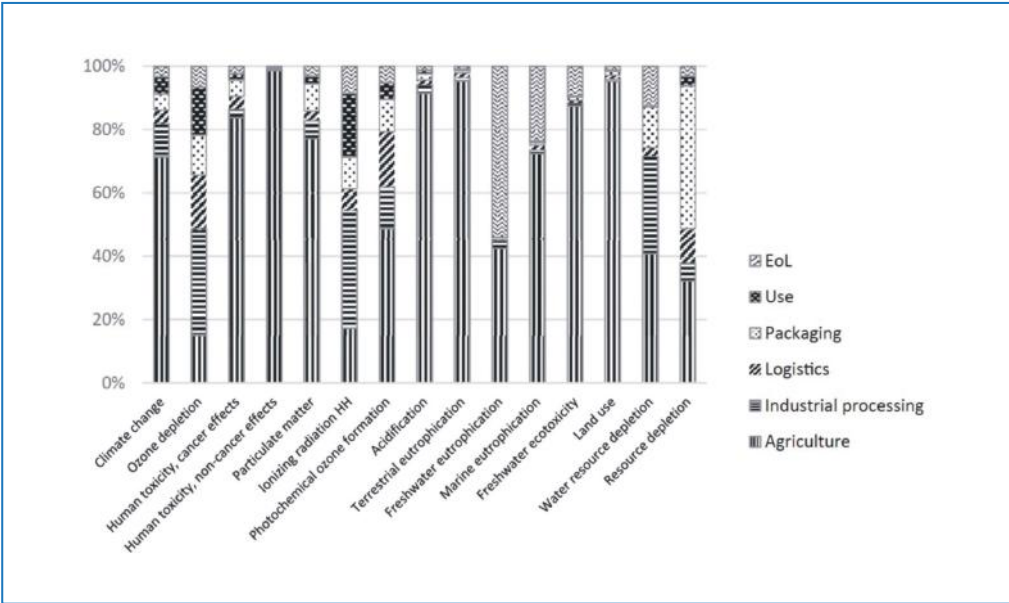
<sup>17</sup> Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, E., Tubiello, E., Leip, A. 2021. Food systems are responsible for a third of global anthropogenic GHG Emissions. *Nature Food*, 2, 198–209. <https://doi.org/10.1038/s43016-021-00225-9>

<sup>18</sup> FAO. 2021. Food systems account for more than one third of global greenhouse emissions. Rome, Italy: United Nations. <http://www.fao.org/news/story/en/item/1379373/icode/>.

<sup>19</sup> Notarnicola, B., Tasselli, G., Renzulli, P.A., Castellani, V., and Sala, S. 2017. Environmental impacts of food consumption in Europe. *J. Cleaner Production* 149: 753-765. <https://doi.org/10.1016/j.jclepro.2016.06.080>.



**Fig. 1.3.** GHG emissions from the food system, total and by areas.  
<https://ourworldindata.org/environmental-impacts-of-food>, Author: Hannah Ritchie



**Fig. 1.4.** Relative contribution of the 6 life-cycle phases to the impact of the entire basket in each impact category for the EU. (Notarnicola, et.al., 2017)<sup>19</sup>. [EoL = End of Life]

**Source:** Bruno Notarnicola, Giuseppe Tassielli, Pietro Alexander Renzulli, Valentina Castellani, S. Sala, 1 January 2017, "Environmental impacts of food consumption in Europe", Journal of Cleaner Production, Elsevier, CC-BY-NC-ND 4.0

<https://www.sciencedirect.com/science/article/pii/S0959652616307570>  
Direct URL: [https://ars.els-cdn.com/content/image/1-s2.0-S0959652616307570-gr2\\_lrg.jpg](https://ars.els-cdn.com/content/image/1-s2.0-S0959652616307570-gr2_lrg.jpg)

## 2.1. The Food and Agricultural System: a definition and challenges for the future?

The FAS can be defined as the way social groups organise to access food<sup>20</sup> and this concept helps characterising the complexity of food related issues. *Fig. 1.5.* provides a conceptual framework for analysing and designing the FAS. The High-Level Panel of Experts of the UN Committee on World Food Security (HLPE/CFS) has proposed that the FAS “gathers all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socio-economic and environmental outcomes”<sup>21, 22</sup>. To escape the assumption that food consumption would rely on rational choices that optimally articulate supply and demand, the framework introduces the notion of food environment, defined as “the physical, economic, political and socio-cultural context in which consumers engage with the FAS to make their decisions about acquiring, preparing and consuming food”<sup>23</sup>. Food environment is thus a social and cultural construct that shapes the FAS and makes it specific from one place to another.

The challenge faced by food production has become increasingly more complex in the 21<sup>st</sup> century than what it seemed to be in the preceding one. In the 20<sup>th</sup> century, indeed, any increase in productivity and production would both contribute to addressing the supply needs in order to cope with the demographic transition and at the same time sustain economic growth because of increasing demand. As explained above, it now lies at the heart of a complex nexus bringing together health, the environment, energy, and economic and social drivers. In addition, as the agricultural sector is both a consumer and supplier of energy<sup>24</sup> interactions between the agricultural and energy sectors and climate change are incredibly complex and context specific. FAS is thus pivotal in bringing together energy and sustainability concerns. Understanding such challenges and actions thus requires system and transdisciplinary approaches. Among others, the systems approach – a multi-level treatment with dynamic interaction between framework constituents – to the analysis and optimisation of these cross-disciplinary issues is gaining traction<sup>25</sup>. From the perspective of data analysis, artificial neural network applications have also proved to be useful approaches in these complex food-agriculture systems, as evidenced by recent developments<sup>26, 27</sup>. Artificial intelligence is thus playing an increasingly relevant role in providing advanced and affordable technological solutions to the FAS.

## 2.2. Sustainable Development Goals and the Food and Agriculture System

Because of their many interactions, food and agriculture systems can be considered as major levers to address all sustainability concerns of the 2030 Agenda for sustainable development (*Fig. 1.5.*), and not just its second Sustainable Development Goal (Zero Hunger). This has also led the UN Global Sustainable Development Report to identify food systems and nutrition patterns as one of the six entry points to achieve the 2030 Agenda<sup>28</sup>. This is why the UN Secretary General called for a Food System Summit (and not just about food) which was held in September 2021. The Summit confirmed how and why food systems bring together the issues of food security, human and ecosystem health, climate change, social justice and political stability.

<sup>20</sup> Malassis L., 1994. Nourrir les hommes. Paris, Flammarion (coll. “Dominos” 16).

<sup>21</sup> HLPE, 2014. Food losses and waste in the context of sustainable food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 2014. <https://www.fao.org/3/i3901e/i3901e.pdf>.

<sup>22</sup> HLPE, 2017a. Nutrition and food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. Retrieved from <https://www.fao.org/3/i7846e/i7846e.pdf>

<sup>23</sup> HLPE, 2017a. Nutrition and food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. Retrieved from <https://www.fao.org/3/i7846e/i7846e.pdf>

<sup>24</sup> HLPE, 2013. Biofuels and food security. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 2013. <https://www.fao.org/3/i2952e/i2952e.pdf>

<sup>25</sup> Borman G.D., de Boef, W.S., Dirks, F., Gonzalez, Y.S., Subedi, A., Thijssen, M.H., Jacobs, J., Schrader, T., Boyd, S., ten Hove, H.J., van der Maden, E., Koomen, I., Assibey-Yeboah, S., Moussa, C., Uzamukunda, A., Daburon, A., Ndambi, A., van Vugt, S., Guijt, J., Kessler, J.J., Molenaar, J.W., van Berkum, S. 2022. Putting food systems thinking into practice: Integrating agricultural sectors into a multi-level analytical framework. *Global Food Security*, 32, 100591. <https://www.sciencedirect.com/journal/global-food-security/vol/32/suppl/C>.

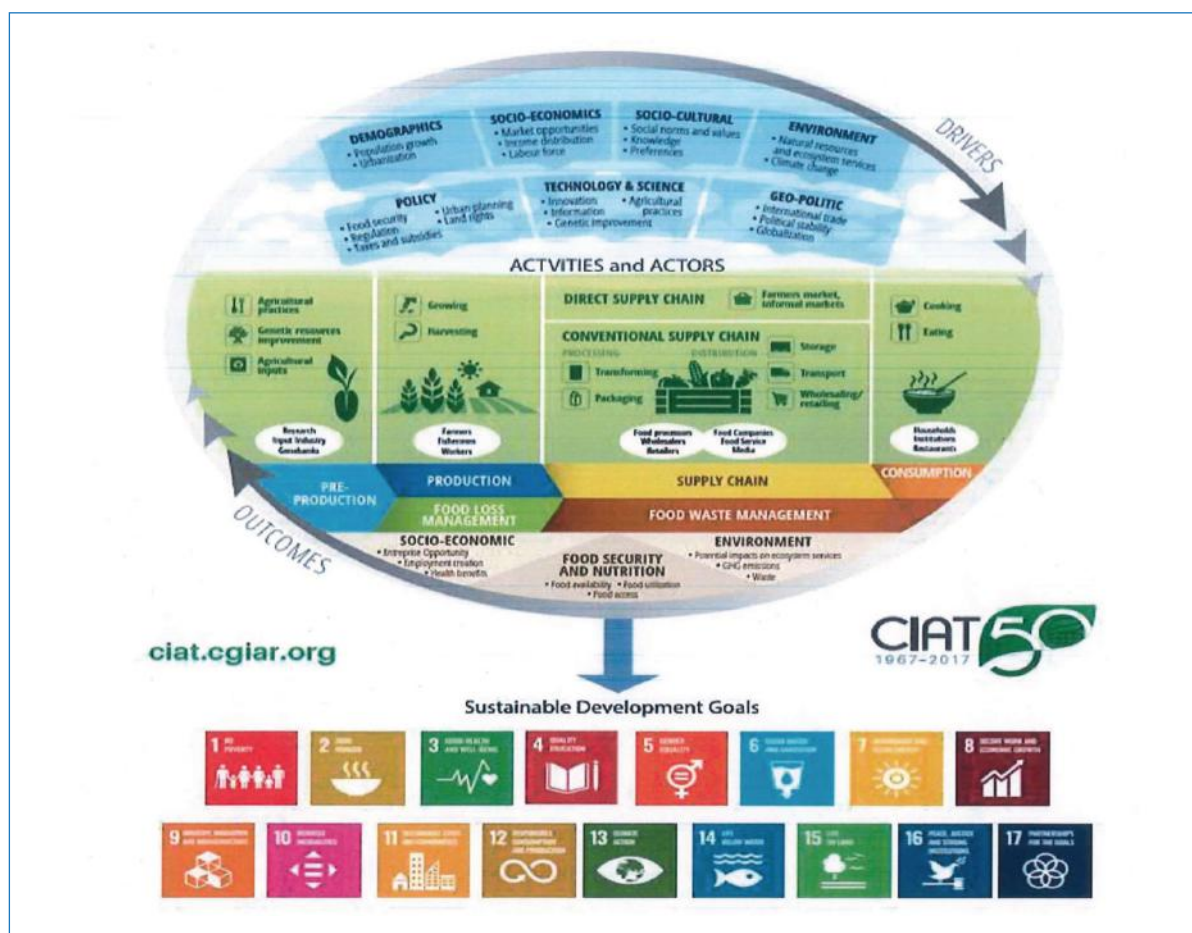
<sup>26</sup> Kujawa, S., Niedbala, G., 2021. Artificial Neural Network in Agriculture, *Agriculture* 11, 497 (and other papers in this Special Issue). <https://www.mdpi.com/2077-0472/11/6/497>; Jimenez, D., Perez-Urbe, A., Satizabal, H., Barreto, M., Van Damme, P., Tomassini, M., 2008., A Survey of Artificial Neural Network-Based Modeling in Agroecology, in *Soft Computing Applications in Industry*. Prasad B (ed), p247. Springer-Verlag, Berlin. [https://link.springer.com/chapter/10.1007/978-3-540-77465-5\\_13](https://link.springer.com/chapter/10.1007/978-3-540-77465-5_13).

<sup>27</sup> Jimenez, D., Perez-Urbe, A., Satizabal, H., Barreto, M., Van Damme, P., Tomassini, M., 2008., A Survey of Artificial Neural Network-Based Modeling in Agroecology, in *Soft Computing Applications in Industry*. Prasad B (ed), p247. Springer-Verlag, Berlin. [https://link.springer.com/chapter/10.1007/978-3-540-77465-5\\_13](https://link.springer.com/chapter/10.1007/978-3-540-77465-5_13)

<sup>28</sup> United Nations, New York, 2019. Global Sustainable Development Report 2019: The Future is Now – Science for Achieving Sustainable Development. 24797GSDR\_report\_2019.pdf (un.org).

This situation calls for profound transformations in both consumption and production<sup>29</sup> (HLPE, 2020), in terms of patterns and volumes as well as energy consumption and related practices. Caron et. al. (2018)<sup>7</sup> indeed calls for a profound transformation of food systems that should include four components:

- The consideration of climate change concerns;
- The promotion of healthy and sustainable consumption patterns, including diet change towards eating balanced diets featuring plant-based foods with lower-emission proteins and lower animal-sourced food to produce sustainably in low greenhouse gas emission systems<sup>30, 31</sup>, and including the reduction of food loss and waste<sup>31, 32</sup>;
- The contribution to the viability and sustainability of ecosystems, including soil health and better fertilisation practices; and
- A renaissance of rural territories.



**Fig. 1.5.** An Interpretation of the Food and Agriculture System illustrating Drivers, Activities, Actors and Outcomes. All elements of growing, harvesting, storing, processing, distributing, consuming and managing the food and agriculture system are encompassed by UN's Sustainable Development Goals (SDGs). Adapted from CIAT, International Center for Tropical Agriculture<sup>33</sup>

Source – Adapted from: International Center for Tropical Agriculture – CIAT

<https://ciat.cgiar.org/about/strategy/sustainable-food-systems/>

<sup>29</sup> HLPE. (2020). Food Security and nutrition building a global narrative towards 2030. Vol. 15. High Level Panel of Experts on Food and Nutrition of the CFS-Committee on World Food Security. (pp. 112). Retrieved from <https://www.fao.org/3/ca9731en/ca9731en.pdf>

<sup>30</sup> HLPE. 2016. Sustainable agricultural development for food security and nutrition: what roles for livestock? A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

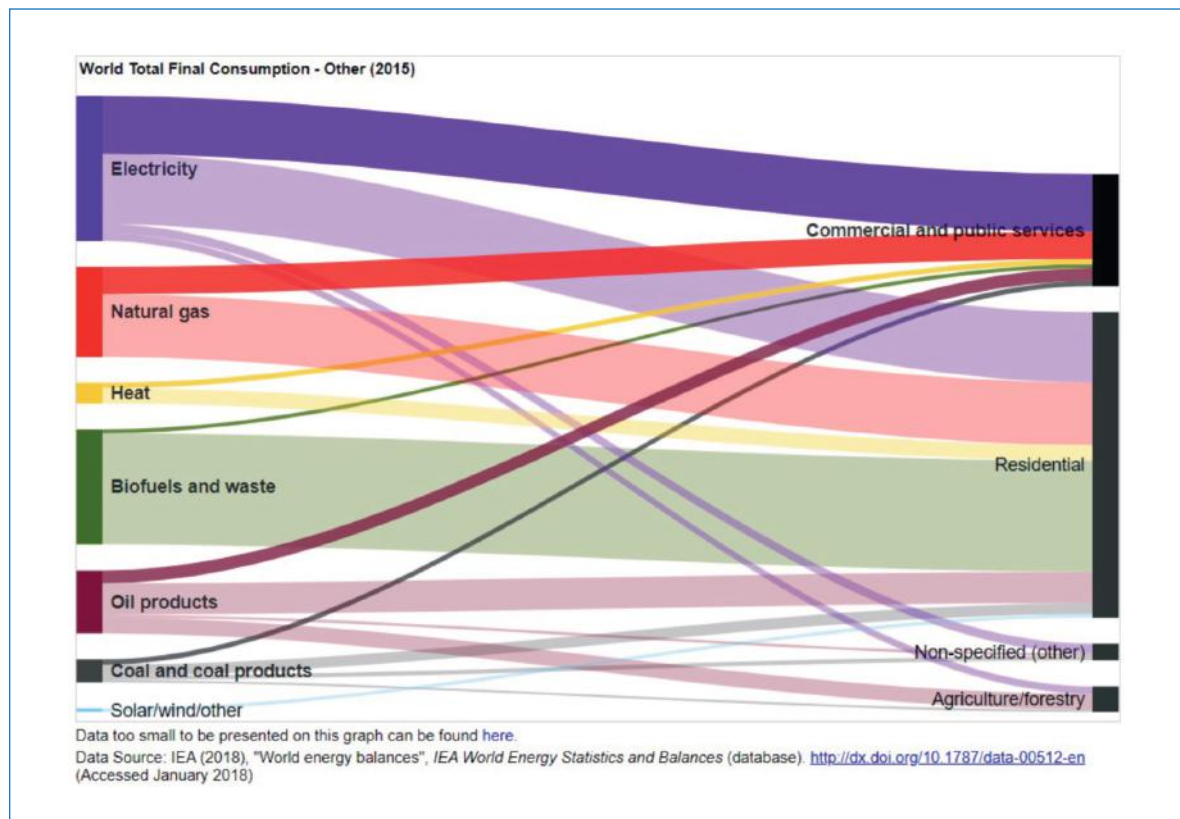
<sup>31</sup> IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

<sup>32</sup> HLPE, 2014. Ibid.; IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

<sup>33</sup> CIAT, 2017. <https://ciat.cgiar.org/about/strategy/sustainable-food-systems/>.

### 2.3. Energy sources ‘fuelling’ the current FAS

The FAS is both a provider and a consumer of energy and the relationship between biofuels and food security is especially challenging. Despite the rapid and intense increase in energy consumption at the production stage, the share in world energy consumption remains marginal, compared to other sectors (*Fig. 1.6.*). *Fig. 1.7.* shows that approximately a 25% of total energy use in High GDP countries occurs in the production stage, 45% in food processing and distribution, and 30% in retail, preparation and cooking in the developed world (IRENA and FAO, 2019). As illustrated by *Fig. 1.8.*, the amount of energy consumed for preparation and cooking may vary tremendously from one country to another. It should be noted that global FAS is becoming more energy intensive in the sectors of processing, packaging, retail and distribution where emissions are growing in some developing countries. Refrigeration and packaging, each contribute about 5% of global food-system emissions<sup>34</sup>. However, emissions can vary substantially by product within the food supply chain.



**Fig. 1.6.** World total energy consumption by the different sectors (IEA, 2018)

<sup>34</sup> FAO. 2021. Food systems account for more than one third of global greenhouse emissions. Rome, Italy: United Nations. <http://www.fao.org/news/story/en/item/1379373/icode/>.

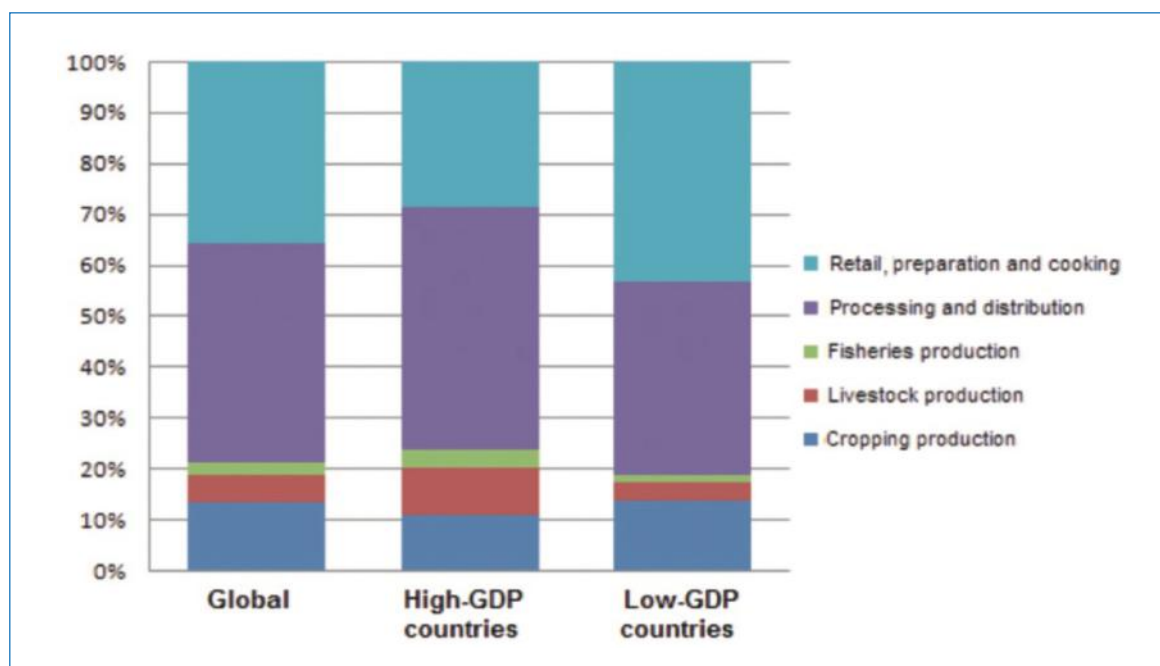


Fig. 1.7. Distribution of shares of end-use total energy across the food supply chain for global consumption ( $2.64 \times 10^{12}$  kWh) and high-GDP ( $1.39 \times 10^{12}$  kWh) and low-GDP ( $1.25 \times 10^{12}$  kWh) FAO (2011)<sup>35</sup> Energy smart food for people and climate, Issue Paper <https://www.fao.org/3/i2454e/i2454e.pdf>

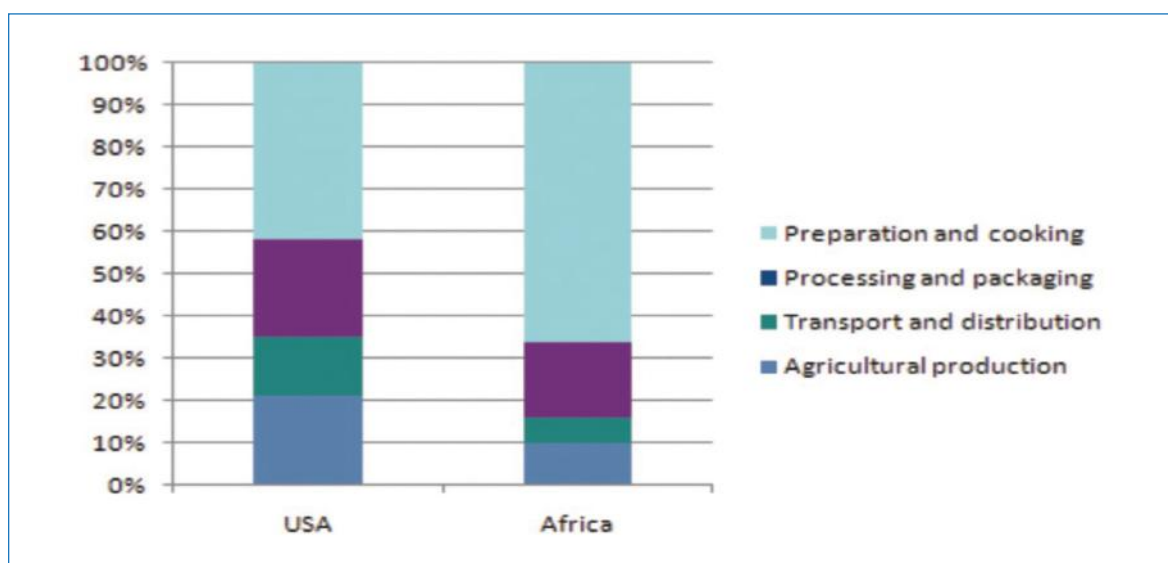


Fig. 1.8. High-GDP and low-GDP differences in energy inputs in the food supply chain. FAO (2011)<sup>35</sup> Energy smart food for people and climate, Issue Paper <https://www.fao.org/3/i2454e/i2454e.pdf>

With the exception of subsistence farming, that depends on human labour and animal power, fossil resources account for roughly 80% of the total global energy consumption for the FAS. For example, in the United States of America, about 93% compared to 86% for the country as a whole of the agri-food chain energy consumption was attributed to fossil fuels in 2007, compared to 86% in nationwide energy utilisation<sup>36</sup>.

<sup>35</sup> FAO. 2011. Global food losses and food waste: Extent, causes, and prevention, Rome, Italy: United Nations. <http://www.fao.org/3/mb060e/mb060e00.htm>

<sup>36</sup> C Canning, P., Rehkamp, S., Waters, A., & Etemadnia, H. 2017. The role of fossil fuels in the US food system and the American diet. USDA Economic Res. Rept. #224, Jan 2017.

Fig. 1.9. illustrates the points along the agri-food chain where interventions can take place to improve energy efficiencies and the implementation of new technologies. One traditional key renewable component in the energy supply of the food and agriculture sector is biomass energy (via biogas production from agriculture and forestry residues). It is used for heating, vehicular operation, and electricity supply (fed to the national grid or from stand-alone off-grid/mini-grid systems). Other renewable sources like wind, solar, hydropower and geothermal forms, vary by country (depending on national renewable energy policies and on the availability of the respective sources).

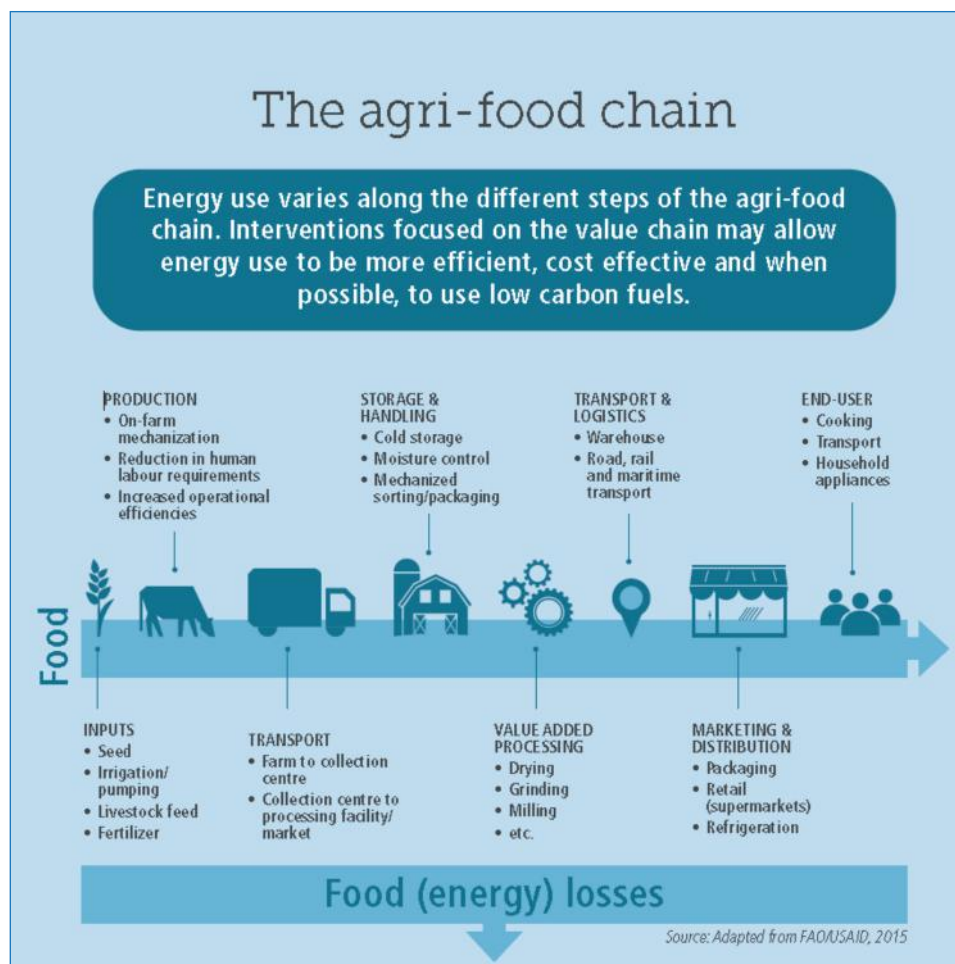


Fig. 1.9. Energy ports along the food-agriculture sector supply chain

Source: Tweet Food and Agriculture Organisation

"Adapted from FAO/USAID, 2015"

<https://twitter.com/fao/status/987069593238851585>

Over the past three decades, there has been a 15% increase in average global GHG emissions as a result of energy use, and within Africa, Asia and Latin America increases of up to 50%<sup>37</sup>. As noted, the American FAS is driven almost entirely by non-renewable energy sources and accounts for approximately 11% of the total energy consumption in the United States<sup>38</sup>. About 60% of this energy is consumed directly via the use of gasoline, diesel, electricity, and natural gas, while the rest of it (about 40%) is consumed indirectly as it is due to the production of fertilisers and pesticides.

<sup>37</sup> FAO. 2022 Agrifood chains I Energy. [www.fao.org/energy/agrifood-chains/en/](http://www.fao.org/energy/agrifood-chains/en/)

<sup>38</sup> C Canning, P., Rehkamp, S., Waters, A., & Etemadnia, H. 2017. The role of fossil fuels in the US food system and the American diet. USDA Economic Res. Rept. #224, Jan 2017. <https://www.ers.usda.gov/webdocs/publications/82194/err-224.pdf>.

### 3. Technologies and their potential for decarbonisation

The FAS is a multiple input-multiple output (MIMO) energy and food production system, i.e. a system of systems. Many strategies are available to adapt agriculture, water, food, energy, and the environment nexus and to make it sustainable. They may rely on technologies that relate to consumption, to production and processing, to the optimisation of resources, including new modes of circular bioeconomy and soilless or lab-grown production approaches, such as vertical farms, insect farming or the cell factory. They may also rely on the application of new tools of computer science combined with synthetic biology that makes it possible to contribute to decarbonisation, while envisaging simpler, cheaper production with limited use of agrochemicals, less land, less water, and better yields than in conventional production. It is also noted that the food and agriculture system of production was historically land based. Food engineering was derived from it. With the evolution of new and emerging synthetic biologically derived foods, however, chemical engineering has taken on a heightened role in these new advances<sup>39, 40</sup>.

Beyond the questions of consumer acceptability of these unconventional foods and confirmation of environmental, ethical, social, and political implications, numerous hurdles remain to be addressed. These include, for example, the selection and improvement of adapted strains, varieties or species, and the development and standardisation of new and disruptive foods. These hurdles go along with controversies regarding food safety and health, environmental impact (particularly in terms of energy balance between consumption and production), and finally the economic, ethical, social, societal, and regulatory consequences.

Below are some examples that illustrate the diversity of such technologies and some of the questions related to their application and implementation.

#### 3.1. Reducing emissions and shifting diets through technology

As shown in Fig. 1.10., reducing growth in demand for food and other agricultural products would contribute to minimising one third of FAS GHG-related emissions. The figure presents a suite of best practice solutions, behaviour change and policy options to accomplish significant reductions in emissions.

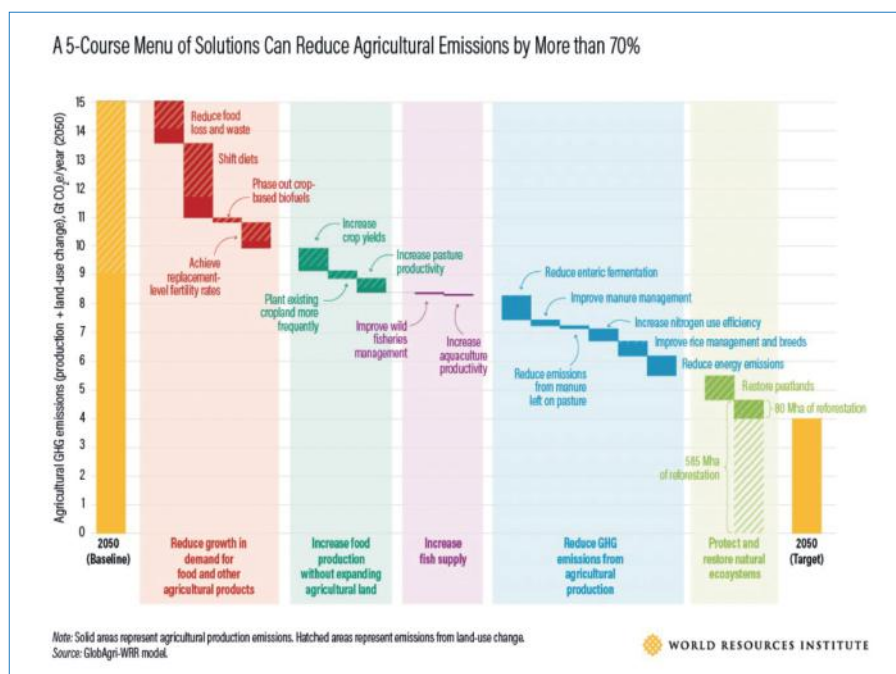


Fig. 1.10. Items suggested to reduce emissions within the production component of the FAS illustrating existing best practices, behaviour change and possible policy options<sup>41</sup>

<sup>39</sup> Hefft, D. I., & Higgins, Seamus. 2021. Food industry and engineering—Quo vadis? Journal of Food Process Engineering, 44(8). <https://doi.org/10.1111/jfpe.13766>.

<sup>40</sup> Hefft, D. I., & Higgins, Seamus. 2022. Re-engineering the Food Industry: Where Do We Go from Here? In C. Hong & W. W. K. Ma (Eds.), Applied Degree Education and the Future of Learning. Springer. [https://doi.org/10.1007/978-981-16-9812-5\\_2](https://doi.org/10.1007/978-981-16-9812-5_2)

<sup>41</sup> World Resources Institute. 2019. Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2025. Final report. July 2019; Chapter 23 [https://research.wri.org/sites/default/files/2019-07WRR%20Food%20Full%20Report\\_O.pdf](https://research.wri.org/sites/default/files/2019-07WRR%20Food%20Full%20Report_O.pdf).

The IPCC (2022)<sup>42</sup> states that there is medium confidence that shifting toward sustainable healthy diets would have a technical potential in the full value chain including the saving of 3.6 (0.3-8.0) GtCO<sub>2e</sub>/yr of which 2.5 (1.5-3.9) GtCO<sub>2e</sub>/yr is viewed as plausible based on a range of GWP<sub>100</sub> value for CH<sub>4</sub> and N<sub>2</sub>O. When accounting for diverted agricultural production only, the feasible potential is 1.7 (1 – 2.7) GtCO<sub>2e</sub>/yr. A shift to more sustainable and healthy diets is generally feasible in many regions. However, the potential varies across regions as diets are location- and community- specific, and may thus be influenced by local production practices, technical and financial barriers and associated livelihoods, everyday life and behavioural and cultural norms around food consumption.

### 3.2. Reducing food loss and waste

The issue of global food losses and waste (FLW) is receiving increased attention<sup>43</sup>. *Fig. 1.11.* illustrates that between about 30 to 40% of food produced for human consumption – approximately 1.3 billion tons per year – is either lost or wasted globally. Clearly reduction in FLW will minimise the amount of food needed to feed the growing global population, improve food security and reduce the environmental footprint of food systems.

FLW refers to the edible parts of plants and animals produced for human consumption that are not ultimately consumed. Food loss occurs at the preharvest stage, during harvesting, through spoilage, spilling or other unintended consequences due to limitations in agricultural infrastructure, storage, and packaging<sup>44</sup>. Food waste typically takes place at distribution (retail and food service) and consumption stages in the food supply chain and refers to food appropriate for human consumption that is discarded or left to spoil<sup>45</sup>.

Interestingly, food waste is greatest in the developed countries while losses are greatest during harvest and postharvest stages for developing countries.

It is important to note that consumer food waste has a greater carbon, GHG, land-use, water, nitrogen, or energy footprint than a similar mass of postharvest loss. This is due to the inclusion of transport, packaging, processing, distribution, and preparation at home, all of which is finally “embedded” in consumer waste. For instance, on average, energy “waste” from consumer waste is equivalent to eight times that resulting from postharvest loss<sup>46</sup>.

Options that could reduce FLW include: (i) investing in harvesting and postharvesting technologies in developing countries, (ii) improved practices in production and postharvest, (iii) behavioural change by businesses and consumers, (iv) improved coordination in the supply chain, as well as enhanced relationships with other actors, (v) improvement in food processing and valuing food by-products, and (vi) development of new policies<sup>47</sup>.

<sup>42</sup> IPCC -AR6- WGIII. 2022. Chapter 7. Agriculture, Forestry and Other Land Uses

<sup>43</sup> NASEM. (National Academies of Sciences, Engineering, and Medicine). 2019b. Reducing impacts of food loss and waste: proceedings of a workshop. Washington, DC. The National Academies Press. <https://doi.org/10.17226/25396>

<sup>44</sup> P Parfitt, J., Barthel, M. & Macnaughton, S. 2010. Food waste within food supply chains: quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1554): 3065–3081.

<sup>45</sup> HLPE, 2014. *ibid*

<sup>46</sup> Dobbs, R., Oppenheim, J., Thompson, F., Brinkman, M., Zornes, M. 2011. Resource revolution: meeting the world's energy, materials, food, and water needs. McKinsey Global Institute ([http://www.mckinsey.com/insights/energy\\_resources\\_materials/resource\\_revolution](http://www.mckinsey.com/insights/energy_resources_materials/resource_revolution)).

<sup>47</sup> HLPE, 2014. *Ibid*

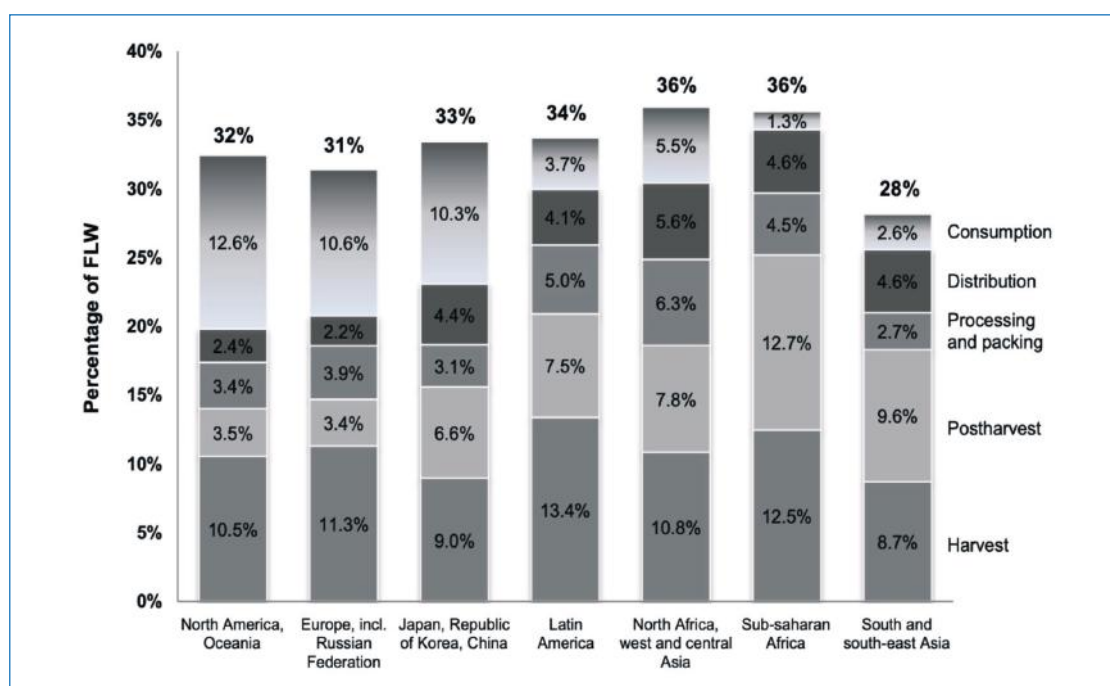


Fig. 1.11. Distribution of FLW along the food chain in the different regions of the world (HLPE, 2014)<sup>45</sup>

The IPCC (2022) estimates, with medium confidence, that reduced FLW has a large global technical mitigation potential of 2.1 (0.1-5.8) GtCO<sub>2e</sub>/yr including savings in the full value chain using GWP<sub>100</sub> and a range of IPCC values for CH<sub>4</sub> and N<sub>2</sub>O. They suggest potential plausible values as 3.7 (2.2-5.1) GtCO<sub>2e</sub>/yr.

### 3.3. Valuing new food resources through technology

Global meat consumption is estimated to increase 3% per year to 2040<sup>48, 49</sup>. However, several groups<sup>49, 50</sup> forecast major changes in the conventional animal-agriculture system, with foods being engineered at the molecular level leading to at least 50% less conventional meat and dairy consumption by 2040.

Alternatives to animal-sourced proteins increasingly open and broaden avenues for exploration, particularly so in developed countries where meat has a strong negative impact (Fig. 1.2.) in terms of GHG emissions and health<sup>51, 52</sup>. More generally, landless food systems have gained traction during the last decade. We are witnessing significant new biological/biochemistry efforts aimed at creating food from plants or animal cells from the 'bottom up'. Three technologies are characterised as: (i) plant-based alternative foods, (ii) cell-cultured/cultivated foods, and (iii) 3D printed foods. Because they use biochemical building blocks from proteins, carbohydrates, fats, and oils from plants and animals, it is a 'new' agriculture.

While much hype has been on synthetic burgers<sup>53</sup> there has been substantial advancement in other alternative foods, such as eggs, fish, shrimps, milk, yogurt, chicken nuggets, and chicken tenders to mention a few of them. The objective of synthetic biology is to develop food products that mimic traditional foods with significant benefits. Such benefits may be: (i) a production environment unaffected by weather/extreme weather; (ii) year-round production; (iii) shortened growing cycles and higher yields; (iv) reduction in land and water use; (v) lower food loss and waste; (vi) shorter supply chains, local access compatible with urban settings;

<sup>48</sup> FAO. 2011. Energy-Smart Food for People and Climate Issue Paper Rome: Food and Agriculture Organization. <https://www.fao.org/3/i2454e/i2454e.pdf>; FAO. 2011. Global food losses and food waste: Extent, causes, and prevention, Rome, Italy: United Nations. <http://www.fao.org/3/mb060e/mb060e00.htm>;

<sup>49</sup> A.T. Kearney.2020. How Will Cultured Meat and Meat Alternatives Disrupt the Agricultural and Food Industry? <https://www. Kearney.com/documents/291362523/291366693/When+consumers+go+vegan%2C+how+much+meat+will+be+left+on+the+table+for+agribusiness+%282%29.pdf/fe61e117-356c-6f4e-2f8e-079dab3e5647?t=1608631513000>.

<sup>50</sup> Tubb, C., and Seba, T. 2019. Rethinking food factory: The next generation indoor and agriculture 2020-2030: The second domestication of plants and animals, the disruption of the cow, and the collapse of industrial livestock farming. [www.rerhinkx.com](http://www.rerhinkx.com).

<sup>51</sup> HLPE. 2016. Sustainable agricultural development for food security and nutrition: what roles for livestock? A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. [https://www.fao.org/fileadmin/user\\_upload/hlpe/hlpe\\_documents/HLPE\\_Reports/HLPE-Report-10\\_EN.pdf](https://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/HLPE_Reports/HLPE-Report-10_EN.pdf).

<sup>52</sup> FAO. 2006. Livestock's long shadow. Environmental issues and options, by H. Steinfeld, P. Gerber, T. Wassenaar, V. Castel, M. Rosales & C. de Haan. Rome. 464 p.

<sup>53</sup> Purdy, C. 2020. Billion Dollar Burger. Penguin Random House. 252 p.

(vii) reduction or elimination of pesticides and antibiotics; (viii) reduction of GHG emissions; (ix) reduction in water pollution; (x) potential for enhanced micronutrients, and (xi) removal of animal welfare concerns (growing conditions and slaughter).

However, there are potential uncertainties and questions, such as: (i) high capital cost; (ii) timeline to market; (iii) in some cases, high energy consumption; (iv) consumer acceptance; (v) concern about food quality and safety, particularly nutritional content and presence of growth hormones; (vi) price to consumers, (vii) potential contamination; (viii) impact and possible detrimental effect for small farmers and for employment; (ix) proprietary nature of processes; (x) unproven technology, and (xi) whether these new landless systems benefit large-scale economies to the detriment of markets for small farmers<sup>54, 55, 56</sup>.

Sustainability is critical to any future food system and is a driving force for these alternative food systems. In broad terms, they seek to develop foods that impose less environmental impact, enhance human health, and reduce the ethical implications of traditional animal-agriculture production, particularly for meat.

It should also be noted that food cost to the consumer is a crucial issue for any new product to be successfully adopted. Over the past 5 to 10 years, numerous entrepreneurs, start-ups, and food companies have created alternative foods that are already in the marketplace. In many cases, the price to consumers, at present, is higher than equivalent traditional foods, but the difference has decreased over time. As these emerging alternative products are improved, it is possible that cost to the consumer will be reduced to be comparable or even less.

### 3.3.1. Plant-based alternative food

Globally the food and agricultural system is estimated, as previously mentioned, to generate around 1/3 of total GHG emissions with 71% from agriculture and related land use and land use change<sup>57</sup>. The opportunity for plant-based alternatives to substantially reduce environmental impacts was determined in a comparative study (Life Cycle Assessment-LCA) of the *Beyond Burger* and a U.S. beef burger (quarter pounder) by the Center for Sustainable Systems at the University of Michigan<sup>58</sup>. The selected parameters were GHG emissions, cumulative energy use, water use, and land use. The comparison was made to an LCA study by the National Cattleman's Beef Association<sup>59</sup>. For the *Beyond Burger* system the results showed 90% less GHG emissions, with 46% less energy, 99% less water and 93% less land use. *Impossible Foods* also commissioned a study (Khan et.al., 2019)<sup>60</sup> which found that the *Impossible Burger* uses 96% less land, 87% less water and 89% less global warming potential than a quarter pound beef burger. Independent LCA studies would be beneficial, given the rapidly changing ingredients being used to create plant-based meat alternatives.

Plant-based protein sources (legumes and cereal grains) are an important choice for both the vegetarian and traditional meat consumer. However, challenges remain for developers of plant-based proteins to deliver a healthy, nutritionally safe, tasty flavour, texture, and appearance (colour) comparable to traditional products. Comparisons yield a mixed story because plant-based meats provide about the same calories as traditional meat with more sodium, more potassium (which helps eliminate sodium), no cholesterol, more iron, more B vitamins, more calcium, and more saturated fat. Thus, there is a need to assess whether plant-based protein would be any less safe or safer than traditional meat and of similar nutritional quality.

<sup>54</sup> Purdy, C. 2020. Billion Dollar Burger. Penguin Random House. 252 p Purdy, 2020; NASEM, 2019; He, C., Zhang, M., Fang, Z. 2019. 3D Printing of food: Pretreatment and post- treatment of materials. Critical Reviews in Food Science and Nutrition, 60(14):2379-2392 <https://doi.org/10.1080/10408398.2019.1641065>.

<sup>55</sup> NASEM. (National Academies of Sciences, Engineering, and Medicine). 2019a. Innovations in the Food System: Exploring the Future of Food. Proceedings of a Workshop. National Academies Press. Washington, DC <http://nationalacademies.org/hmd/Activities/Nutrition/FoodForum/2019-AUG-07>

<sup>56</sup> He, C., Zhang, M., Fang, Z. 2019. 3D Printing of food: Pretreatment and post- treatment of materials. Critical Reviews in Food Science and Nutrition, 60(14):2379-2392 <https://doi.org/10.1080/10408398.2019.1641065>

<sup>57</sup> Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, E., Tubiello, E., Leip, A. 2021. Food systems are responsible for a third of global anthropogenic GHG Emissions. Nature Food, 2, 198–209. <https://doi.org/10.1038/s43016-021-00225-9>.

<sup>58</sup> Heller, M., Keoleian, G. 2018. Beyond Meat's beyond burger life cycle assessment: A detailed comparison between a plant-based and animal-based protein source. Report No.CSS18-10. Center for Sustainable Systems, University of Michigan, Ann Arbor 1-38..

<sup>59</sup> Thoma, G., Putman, B., Matlock, M., Popp, J., English, L. 2017. Sustainability Assessment of U.S. Beef Production Systems. University of Arkansas Resiliency Center. <https://scholarworks.uark.edu/rescentfs/3>.

<sup>60</sup> Khan, S., Loyola, C., Detting, J., Hester, J. 2019. Comparative environmental LCA of the Impossible Burger with conventional ground beef burger. Report prepared by Quantis for Impossible Foods. [https://assets.ctfassets.net/Hv516v5tsj/43xFx74UoYku640WSF3t/cc2136148ee80fa2d8062ef0012ec56/impossible\\_foods\\_comparable\\_LCA.pdf](https://assets.ctfassets.net/Hv516v5tsj/43xFx74UoYku640WSF3t/cc2136148ee80fa2d8062ef0012ec56/impossible_foods_comparable_LCA.pdf).

### 3.3.2. Cell-cultured food

Cell-cultured meat, also known as cultivated meat, has advanced at a rapid pace over the past 20 years. The concept, although relatively simple, uses animal cells nurtured within a bioreactor to produce food that is designed to mimic meat products<sup>61</sup>. Compared to plant-based protein where protein is extracted from plants, cell-based meat is created from cells extracted from animals and grown in a culture. Specifically, a small piece of fresh muscle, obtained by biopsy, from a living animal is stimulated by a combination of mechanical and enzymatic methods to produce stem cells<sup>62</sup>.

Using culturing methods, the adult stem cells (called satellite cells), in the presence of relatively high serum concentrations, divide, thus leading to multiplying populations. Tissue engineering methods are then used to differentiate these expanded cells into muscle and fat tissue, which leads to the generation of a cultured meat product closely resembling conventional meat. A recent study suggests that it may be possible to grow cultured meat with much less dependence on animals by using a soy-based scaffold to support muscle cells and form a meat-like 3D-cell structure<sup>63</sup>.

A Life Cycle Assessment (LCA)<sup>64</sup> and a (TEA) techno-economic assessment<sup>65</sup> modelled future large-scale cell-cultured meat production facilities and showed reduced overall environmental impacts and the potential to be cost-competitive with conventional meat by 2030. These are the first reports using data collected from active companies (more than 15) in the chain.

The LCA shows cell-cultured meat is about 3.5 times more efficient (feed conversion ratio) than poultry which is the most efficient system of conventional meat production. The LCA in comparison with traditional meat includes the use of renewable energy in which case there is a reduction of 17-92% in GHG emissions, 63-95% in land use and 51-78% in the use of water depending on the respective conventional animal system. Thus, relative comparisons with conventional meat depend on the type of systems used for generating energy (i.e., decarbonised, and renewable) and the specific animal production system. In addition, exploring such avenues raises some ethical, cultural, and religious issues.

### 3.3.3. 3D-printed food

The combination of robotics and software has entered the realm of food manufacturing in the form of 3D printing<sup>66, 67, 68, 69</sup>. 3D printing technology is a novel approach which can create complex geometries, tailored textures, and nutritional contents. The 3D technology can provide 'customised food' to meet special dietary needs as well as mass customisation.

In the 3D-printing process, food ingredients are placed in cartridges, and the product is created layer by layer by a controlled robotic process, like the 3D printing of non-food items. The technology has been employed to use tissue engineering in order to create meat and other food alternatives. The 3D technology has also been employed at the home scale to create 'designer' foods. Depending on the specific food, ingredients can range from processed components (sauces, dough, etc.) to more elemental ingredients such as sugars, proteins, fats, and carbohydrates<sup>69</sup>. Some foods may require further processing, such as some form of cooking or storage. A significant challenge is to link material properties and structure to printing process variables to obtain the desired 3D-printed product. The parameters of control are those relating to the printer and those controlling the food-relevant parameters. Thus, it seems not to be a great stretch to infer that 3D printing will lead to designer and specialised food products. The 3D-printing process compresses the value chain to a highly local

<sup>61</sup> Boler, D., Martin, J., Kim, M., Krieger J., Milkowski, A., Mozdziak, P., Sylvester, B. 2020. Producing food products from cultured animal tissues. [www.cast-science.org/wp-content/uploads/2020/04/QTA2020-1-Cultured-Tissues-1.pdf](http://www.cast-science.org/wp-content/uploads/2020/04/QTA2020-1-Cultured-Tissues-1.pdf).

<sup>62</sup> Post, M. 2013. Cultured beef: Medical technology to produce food. *J. Food and Agriculture*. 94(6):1039-1041. Doi:10.1002/jsfa.6474

<sup>63</sup> Young J., Skivergaard, S. 2020. Cultured meat on a plant-based frame. *Nature Food* 1, 195. <https://doi.org/10.1038/s43016-020-0053-6>.

<sup>64</sup> CE Delft. 2021a. LCA of cultivated meat: Future projections for different scenarios. <https://www.cedelft.eu/en/publications/2610/lca-of-cultivated-meat-future>

<sup>65</sup> CE Delft. 2021b. TEA of cultivated meat: Future projections of different scenarios. <https://www.cedelft.eu/en/publications/2609/tea-of-cultivated-meat-future>.

<sup>66</sup> Dankar, I., Haddarah, A., Omar, F., Sepulcre, F., Pujola, M. 2018. 3D Printing technology: The new era for food customization and elaboration. *Trends in Food Science & Technology*. 75(231-242). <https://doi.org/10.1016/j.tifs.2018.03.018>;

<sup>67</sup> Yang, F., Zhang, M., Bhandari, B. 2017. Recent developments in 3D food printing. *Critical Reviews in Food Science and Nutrition*, 57:14, 3145-3153. doi:10.1080/10408398.2015.1094732;

<sup>68</sup> He, C., Zhang, M., Fang, Z. 2019. 3D Printing of food: Pretreatment and post-treatment of materials. *Critical Reviews in Food Science and Nutrition*, 60(14):2379-2392 <https://doi.org/10.1080/10408398.2019.1641065>.

<sup>69</sup> Severini, C., Derossi, A., Azzollini, D. 2016. Variables affecting the printability of foods: Preliminary tests on cereal-based products. *Innovative Food Science and Emerging Technologies*. 38(281-291). <http://dx.doi.org/10.1016/j.ifset.2016.10.001>

system made of inputs (ingredients), a single controlled process (the 3D printer) and a single output (the food product) and it can thereby possibly reduce energy and GHG emissions across the value chain.

### 3.3.4. Advanced Greenhouses and Vertical Farms

The concept of growing plants in environmentally controlled areas can be traced back to Roman times<sup>70</sup>. The concept of the greenhouse, as we have come to know it today, began in the Netherlands and then England in the 17<sup>th</sup> century. They evolved from simple row covers to very large structures in the 1960's when materials such as polyethylene films, aluminium extrusions, special galvanised steel, and PVC tubing became available for various structural support frames.

The advanced greenhouse is defined here as a greenhouse with a highly controlled environment, high automation under computer control and uses a soilless growing medium, a hydroponic solution. The controlled environment for plant production consists of an intensive assessment of the environment by numerous sensors to measure and monitor such parameters as: temperature, pH, relative humidity, dissolved O<sub>2</sub> in nutrient solution, electrical conductivity for dissolved salts in nutrient solution, CO<sub>2</sub> of inside air, and light intensity from the sun and supplemental lighting, and PAR (photosynthetic active radiation) in mol/m<sup>2</sup>/d. Quality and optimum plant growth is dependent on plants getting an optimum daily quantity of PAR (mol/m<sup>2</sup>/d). If the daily PAR is not provided by the sun, the computer will implement supplemental lighting to meet the desired value.

An advanced greenhouse consists of a complete system from the germination of seeds to the finished product. Typically, the seed is planted in a fibrous material such as a Rockwool cube to germinate. Following germination, the cubes are inserted into a material (like Styrofoam) to float on the surface of the nutrient solution until fully mature. Temperature will be controlled typically by mechanical fan ventilation under computer control of air flow by managing air intake openings. Where appropriate, evaporative cooling may be used to provide cooling. The addition of CO<sub>2</sub> can be used to increase plant growth. Shading material can be used to reduce excessive solar energy and movable insulation to reduce heat loss at night respectively. Beyond the controlled thermal technologies and growing environment, the advanced greenhouse will include a significant automation for the handling of materials, including the use of robots<sup>71</sup>.

Based on recent developments in advanced greenhouses, the Vertical Farm (VF) uses the vertical dimension (Fig. 1.12.) to grow plants in stacked layers thereby greatly increasing the amount of product grown per unit area<sup>72, 73, 74, 75</sup>. Like for the advanced greenhouse, the growing environment in a vertical farm is closely controlled for temperature, humidity, ventilation, and the properties of the nutrient solution, including the introduction of robotics. Five reasons to take vertical farms seriously are that: the effect of weather and weather extremes is avoided; water usage is largely reduced, by as much as 95%; plant yields are high, and the growing cycle is short; food loss is lower; supply chains are shorter because VFs can be located in urban areas; and products can be produced year-round<sup>76</sup>.

Key challenges for VFs are high capital and energy costs. The issues of high energy consumption in VFs are due to full artificial lighting (LEDs) and for meeting cooling and humidification loads. More efficient LEDs using LEDs tailored to the light spectrum for the specific crop, rather than the full spectrum, may save electricity. Possibly the residual heat could be used in a surrounding case where a source of heat is needed for a closely located enterprise. Clearly, because of large capital costs and energy requirements, VFs will remain a 'niche' system until these issues are resolved. In comparison with advanced greenhouses, where solar energy is utilised and where greenhouses can also be located in urban environments (rooftops and vacant lots for example), VFs would seem to offer uncertain benefits. Efforts to conduct a Life Cycle Assessment of VFs and, in addition, approaches

<sup>70</sup> Janik, J., Paris, H., Parish, D. 2007. The cucurbits of Mediterranean Antiquity: Identification of Taxa from Ancient Images and descriptions. *Annals of Botany* 100(7): 1441-1457. doi:10.1093/aob/mcm242.

<sup>71</sup> Ting, K., Lin, T., Davidson, P. 2016. Integrated urban controlled environment agricultural systems. In: Kozai T, editor. LED lighting for urban agriculture. Springer-Science+Business Media, Singapore. p. 18-36 doi: 10.1007/978-981-10-1848-0\_2.

<sup>72</sup> Benke, K., Tomkins, B. 2017. Future food-production systems: Vertical farming and controlled environment agriculture. *Sustainability: Science Practice and Policy* 13(1): 13-26. <https://doi.org/10.1080/15487733.2017.1394054>

<sup>73</sup> Despommier, D. 2011. *The Vertical Farm: Feeding the World in 21st Century*. Martin's Press. NY, NY. 293 p.;

<sup>74</sup> Kozai, T. (Editor). 2018. *Smart plant factory: The next generation indoor vertical farms*. Singapore: Springer; Kozai, T., Fujiwara K., Runkle, E. 2016. (Editors). 2016. *Plant Factory and Greenhouse with LED Lighting*. Singapore: Springer.

<sup>75</sup> Kozai, T., Fujiwara K., Runkle, E. 2016. (Editors). 2016. *Plant Factory and Greenhouse with LED Lighting*. Singapore: Springer.

<sup>76</sup> Pinstrup-Andersen, P. 2017. Is It Time to take vertical farming seriously? 2017. *Global Food Security*. <https://dx.doi.org/10.1016/j.gfs.2017.09.002>.

for an integration of VFs into cities are critical to assess the future of VFs. Numerous VFs have been developed and a substantial number, as well, are in the planning stages in the United States of America and Asia. Some of these are conceptualised to include solar energy directly, aquaculture and even livestock production<sup>77</sup>.



**Fig. 1.12.** An example of a vertical farm

**Source:** Future Farming. Driscoll's strawberries to be grown in Plenty vertical farm, 14-10-2020  
<https://www.futurefarming.com/smart-farming/driscolls-strawberries-to-be-grown-in-plenty-vertical-farm/>  
 See also: <https://www.plenty.ag/>

### 3.4. Improving food supply through technology

#### 3.4.1. Regenerative agriculture / agroecology / organic agriculture

Agricultural management practices that increase soil organic matter in croplands is the focus of much interest. They include (1) crop management, in the form of, for example: high input carbon practices such as adopting improved crop varieties, crop rotation, the use of cover crops, perennial cropping systems, integrated production systems, crop diversification, agricultural biotechnology; (2) nutrient management, including fertilisation with organic amendments/ green manures; (3) reduced tillage intensity and residue retention; (4) improved water management, including the drainage of waterlogged mineral soils and irrigation of crops in arid/semi-arid conditions, (5) improved rice management (6) and biochar application<sup>78</sup>.

The practices referred to as regenerative agriculture and agroecology, as well as organic agriculture, have been drawing much attention recently. These terms have no universal definitions but are frequently described – regenerative agriculture, as “a land management philosophy whereby farmers and ranchers grow food and fibre in harmony with nature and their communities”<sup>79</sup>; agroecology as “the study of relationships between plants, animals, people, and their environment - and the balance between these relationships”; organic agriculture as “a production system that relies on ecosystem management and does not allow the use of synthetic chemical inputs (inorganic fertilizers and pesticides). It relies on ecological processes and natural sources of nutrients (such as compost, crop residues and manure)<sup>80</sup>”.

Agroecological approaches acknowledge 6 major shifts<sup>81</sup> (see Fig. 1.13.). Both regenerative agriculture and agroecology are commonly perceived to advance: no- or minimum-till farming, cover crops, diverse crop rotations, rotating livestock grazing, and a lessened use of fertilisers, pesticides, and herbicides for the purpose of sequestering carbon and promoting a healthy soil. Cropping system diversification has been shown to reduce the negative environmental impacts of soil erosion and nutrient runoff, and reduced cropping inputs while maintaining crop yields<sup>82</sup>.

<sup>77</sup> Kalantari, F., Tahir, O., Lahijani, A., Kalantari, S. 2017. A review of vertical Farming technology: A guide for implementation of building integrated agriculture in cities. Advanced Engineering Forum 24 (76-91), [doi.10.4028/www.scientific.net/AEEF.24.76](https://doi.org/10.4028/www.scientific.net/AEEF.24.76)

<sup>78</sup> IPCC -AR6- WGIII. 2022. Chapter 7. Agriculture, Forestry and Other Land Uses.

<sup>79</sup> NRDC (National Resources Defense Council). 2022. Regenerative Agriculture: Farm Policy for 21<sup>st</sup> Century. [regenerative-agriculture-farm-policy-21st-century-report-pdf](https://www.nrdc.org/regenerative-agriculture-farm-policy-21st-century-report-pdf).

<sup>80</sup> Page 150 in Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. <https://www.fao.org/3/ca5602en/ca5602en.pdf>.

<sup>81</sup> Caron P., 2021. Agroécologie : saisir les blocages internationaux. In : La transition agroécologique. Quelles perspectives en France et ailleurs dans le monde ? Tome 1. Hubert Bernard (ed.), Couvet Denis (ed.). Paris : Presses des Mines, 131-140. (Académie d'agriculture de France) ISBN 978-2-35671-620-0.

<sup>82</sup> Tamburini, G., Bommarco, R., Wanger, T., Kremen, C., van der Heijden, M., Liebman, and M., Hallin, S. 2020. Agricultural diversification promotes multiple ecosystems services without compromising yield. Sci. Adv. eaba175.

Organic farming can be considered as a form of agroecology and regenerative agriculture because it is guided by similar principles in general, although it is associated with specific regulations. Organic farming is perhaps more noted for its potential co-benefits, such as enhanced system resilience and biodiversity promotion, than for mitigation. While there are similarities across regenerative agriculture and agroecology, there are also important disputes that mainly relate to the polysemy of both terms and to the development models they are supposed to promote, in particular to the respective roles of market and policies<sup>83</sup>.

There is general agreement that regenerative agriculture and agroecology practices improve soil health and provide environmental benefits. Some researchers report<sup>84</sup> that regenerative agriculture practices have limited potential to significantly increase soil carbon sequestration. Nevertheless, some corporations have set up a carbon sequestration market (Bayer) and a carbon credit for soil carbon sequestered (Land O'Lakes) intended for farmers. In addition, Cargill, McDonald's, Nestle, Walmart Foundation and other major companies are collaborating with the World Wildlife Foundation on regenerative practices to improve grasslands of the Northern Great Plains of the U.S. It is suggested that, going forward, farmers will need to be paid for environmental services, in particular soil carbon storage. However, this requires an ability to accurately measure soil carbon and quantify change in the field over time in order to assess the effects of differing practices, as well as institutional arrangements to reward practices. Future research is thus needed to find new ways of soil carbon sequestration and gather data through the measurement of soil carbon content in order to develop a global carbon market.



Fig. 1.13. Towards agroecological approaches<sup>85</sup>

<sup>83</sup> HLPE. 2019. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. <https://www.fao.org/3/ca5602en/ca5602en.pdf>.

<sup>84</sup> IPCC-AR6- WGIII. 2022. Chapter 7. Agriculture, Forestry and Other Land Uses

<sup>85</sup> Caron P., 2021. Agroécologie : saisir les blocages internationaux. In : La transition agroécologique. Quelles perspectives en France et ailleurs dans le monde ? Tome 1. Hubert Bernard (ed.), Couvet Denis (ed.). Paris : Presses des Mines, 131-140. (Académie d'agriculture de France) ISBN 978-2-35671-620-0

Along with the agroecology discussion, a long-standing debate relates to the opposition between land sparing and land sharing. This was initiated to address the Question of whether it is best to make agriculture more biodiversity-friendly by conserving biodiversity within agricultural landscapes (“land-sharing”) or sharply separate the zones managed for biodiversity from those managed for high-intensity agricultural and maximised output (land-sparing). This dichotomy is now disputed as intensification has proved to be a driver for land expansion when strict land tenure regulation is not in place. In addition, and as shown by the HLPE/CFS<sup>86</sup>, “there is no single universal answer to this debate, which originated from questions raised at the global level to address agriculture-driven deforestation- and environment-related concerns. At the local level, avenues to address such concerns, including mixed arrangements, and their impact may vary according to specific biological, ecological, and institutional context.” Finally, the HLPE/CFS challenges the basic “assumptions underlying this apparent dichotomy. First, in terms of whether conservation friendly agricultural practices are necessarily low-yielding and, second, the extent to which the impacts on biodiversity of chemical-intensive agriculture are confined to the areas where it is practiced.”

A specific practice under study in India is the Broad Bed Furrow (BBF) which is proposed to enhance rainfed farming<sup>87</sup>. The goal is to adopt appropriate technology to best manage limited soil moisture in areas of limited rainfall. The BBF system involves the preparation of a broad bed of 90 cm, a furrow of 45 cm and sowing of crop at a row spacing of 30 cm on the bed. The projected benefits are water savings, erosion control, moisture conservation and a channel for drainage in the case of heavy rainfall. Limited results indicated that BBF technology has the potential to increase water productivity for some crops.

Finally, it is noted that the IPCC (2022) states with medium confidence that enhanced soil carbon management of croplands has a global technical mitigation potential of 1.9 (0.4-6.8) GtCO<sub>2</sub>/yr and in grasslands 1.0 (0.2-2.6) GtCO<sub>2</sub>.

### 3.4.2. Nitrogen-use efficiency / optimal nitrogen management

Nitrogen fertiliser plays a critical role in food production globally, but it is also responsible for a variety of environmental problems associated with its loss in various ways. Nitrogen is important for healthy crops, enhancing soil organic carbon, and increasing crop yields. Nitrogen fertiliser is largely, at present, produced using a process called the Haber-Bosch reaction in which hydrogen, primarily from natural gas (via steam reforming - an endothermic reaction), is reacted with nitrogen from air to produce ammonia (NH<sub>3</sub>), the basic building block of all nitrogen fertilisers. This process uses a large amount of fossil energy, approximately 70 MJ/kg (19.4 kWh/kg) depending on the respective plant. Energy thus used in production of nitrogen fertilisers is the largest source of fossil fuel consumption in agriculture, with predictions that it will constitute 2% of global energy use by 2050<sup>88</sup>. Although it will vary by the respective production system for N, the largest component of energy use (as much as 30-40%) is that attributed to making synthetic nitrogen fertilisers.

The production of nitrogen fertiliser (see chapter on Chemicals) and its use in agriculture both generate GHGs and comprises the largest source of ammonia, nitrate, and nitrous oxide pollution globally, with severe impacts on ecosystems, human health, and climate change. If yields are to be the same on a global scale, developed Western countries should use less nitrogen fertiliser and poor countries more according to van Grinsven et. al. (2022)<sup>89</sup>. This study looked at meeting the needs of a reliable food supply, but also at the costs associated with the environmental effects of nitrate leaching, soil depletion and ammonia emissions.

Dealing with nitrogen problems in global agriculture requires a holistic nitrogen and food system approach, balancing risks and opportunities for changes in land use and resource security for agriculture, rural livelihoods, dietary choice, and technology advances. The nutrient stewardship principles of the 4Rs (right source of N fertiliser, right rate, right timing application, and right placement) suggest numerous approaches such as renewable electricity-based fertiliser plants, integrated soil and fertility management of cropping systems,

<sup>86</sup> HLPE. 2019. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. <https://www.fao.org/3/ca5602en/ca5602en.pdf>.

<sup>87</sup> Verma, P.D., Parmanand and Tamrakar, S.K. (2017). Effect of broad bed furrow method for rainfed soybean cultivation at Balodabazar district of Chhattisgarh. *Internat. J. Agric. Engg.*, 10(2) : 297-301, DOI: 10.15740/HAS/IJAE/10.2/297-301.

<sup>88</sup> Harpankar, K. 2020. Optimal Nitrogen Management for Meeting Sustainable Development Goal 2. in *Science, Technology, and Innovation for Sustainable Development Goals*. Editors: Adenle, A., Cheroot, M., Moors, E., and Pannell, D, pg 369-384. Oxford University Press. NY, NY.

<sup>89</sup> Van Grinsven, H.J.M., Ebanyat, P., Glendining, M. et al. 2022. *Establishing long-term nitrogen response of global cereals to assess sustainable fertilizer rates* | *Nature Food*, *Nat Food* 3, 122–132. Correction: <https://www.nature.com/articles/s43016-022-00475-1>

biological nitrogen fixation (for example through CRISPR editing), precision agriculture for placement and nanotechnology coatings for time release of N. Specifically, it is necessary to optimise N application in order to minimise environmental effects while maximising plant uptake without significant reduction in yields. It should be noted that farmers also have to meet supply chain specifications, e.g., protein content. Improved crop nutrient management consisting of these practices and others is estimated by the IPCC (2022), with medium confidence, to have a technical potential of 0.3 (0.06-0.7) GtCO<sub>2e</sub>/year.

“Green” ammonia, produced with hydrogen, obtained from water electrolysis, and nitrogen from the air, in an “all- electric” process, might be an alternative to the fossil fuel-based ammonia production. Where stranded wind and solar energy sources (energy capacity exists but cannot be used or sold) are available in agricultural regions, there could be possibilities for regional small-scale all-electric ammonia projects. Another example could be an integration with bioethanol plants by capturing emissions of CO<sub>2</sub> to react with ammonia and thus produce urea, a more easily stored and applied form of nitrogen fertiliser.

### 3.4.3. Agroforestry

The term agroforestry is applied to land use systems in which perennial woody plants are cultivated on the same area as useful plants and/or livestock<sup>90</sup>. The inclusion of trees or other woody perennials within farming systems is designed to capture the interactive benefits of perennials and/or animals in their use of growth resources (i.e., light, nutrients, water) compared to single-species systems (Lorenz and Lal, 2018)<sup>91</sup>. Lorenz and Lal (2018) classify these systems into agrosilvicultural (crops and trees), silvopastoral (pasture / animals + trees), and agrosilvopastoral (crops + pasture / animals + trees). Agroforestry systems are estimated to cover about 10 million km<sup>2</sup> of agricultural land globally and are most widespread in tropical regions such as Southeast Asia, Latin and Central America, and in the areas of sub-Saharan Africa, where they are often adopted by small land holders. The purpose is to create ecological and economic benefits through the synergy of the individual components (*Fig. 1.14.*).

Trees capture large amounts of atmospheric carbon dioxide (CO<sub>2</sub>) during photosynthesis and transfer a fraction of these to the soil, which may be sequestered. Estimates for the carbon (C) sequestration potential above and below ground over a period of 50 years range between 1.1 and 2.2 Pg (1 Pg = 1Gt = 10<sup>15</sup>g) C/year but these numbers are highly uncertain<sup>91</sup> because of the great diversity of land practices in agroforestry systems. Agroforestry may also enhance biodiversity by creating structural diversity, retreats for animals, as well as water quality benefits. There is however a significant need to develop standard methods and procedures to determine the amount of carbon sequestration from global agroforestry and quantify the system as a low-cost method for environmental benefits.

<sup>90</sup> Schneider, P., Rochell, V., Plat, K., Jaroski, A. 2021. Circular approaches in small-scale food production. *Circular Economy and Sustainability*. 1:1231-1255. <https://doi.org/10.1007/s43615-021-00129-7>.

<sup>91</sup> Lorenz, K., Lal, R. 2018. Agroforestry Systems. In: *Carbon Sequestration in Agricultural Ecosystems*. Springer, Cham. [https://doi.org/10.1007/978-3-319-92318-5\\_6](https://doi.org/10.1007/978-3-319-92318-5_6)

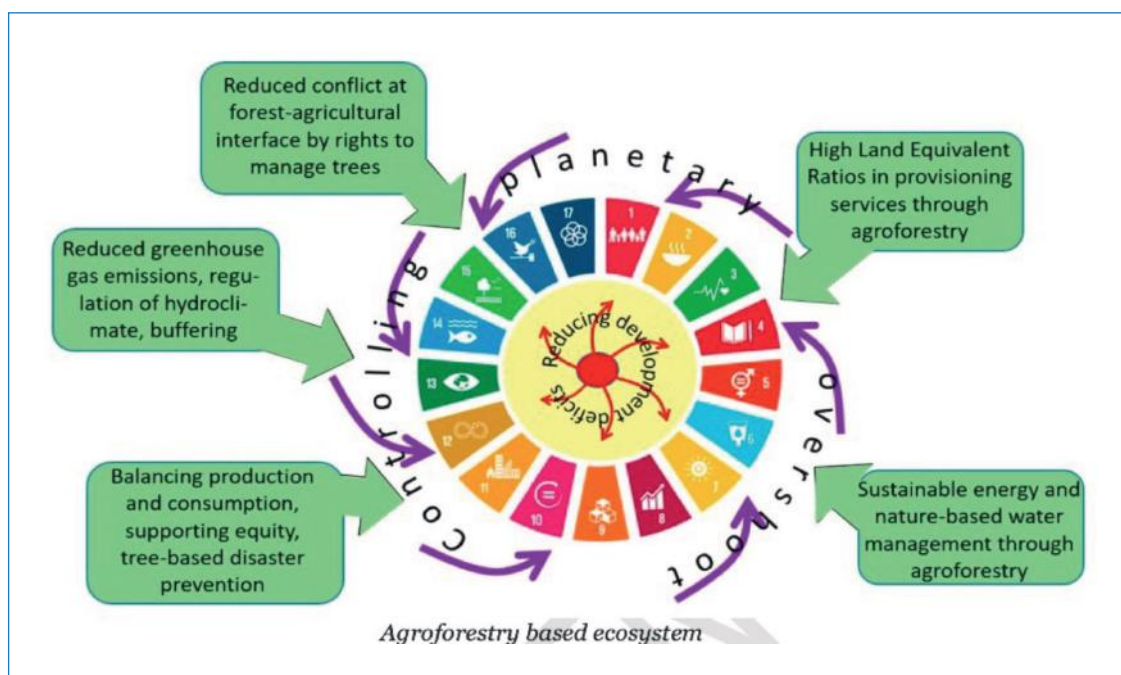


Fig. 1.14. Illustration of agroforestry systems for ecosystem services and economic benefits<sup>92</sup>

Source: Van Noordwijk, M. 2021. Agroforestry-Based Ecosystem Services: Reconciling Values of Humans and Nature in Sustainable Development. *Land* 2021, 10(7),699  
<https://www.mdpi.com/2073-445X/10/7/699>

### 3.4.4. Food manufacturing/processing

Global energy demand for food manufacturing and distribution accounts for approximately 45% of the energy consumption of the FAS. Despite the variability of available data for energy demand, depending on the different products and processes, Ladha-Sabur et.al. (2019)<sup>93</sup> have developed a database for energy consumption. They identified general trends on energy consumption owing to manufacturing and transportation, with attention to the UK food system. The most energy intensive food products are powders (i.e., instant coffee and milk powders), fried goods (French fries and crisps), and bread, which involve thermal processes. Hygiene and sanitary requirements also affect water consumption and waste for meat and dairy. It should be noted that packaging is not included in the report by Ladha-Sabur et al. (2019).

Advances in food processing are emerging with a significant potential impact on reducing energy consumption and GHG emissions in food manufacturing through processes such as high-pressure processing<sup>94</sup>, cold plasma<sup>95</sup>, pulsed electric field<sup>96</sup>, ultrasound<sup>97</sup>, and microwaves<sup>98</sup>. These processes rely on electricity, thus offering the opportunity to replace traditional processes, which have been based on thermal processes using fossil fuels.

In terms of transportation, there are current movements that advocate for a more decentralised/distributed supply chain supporting local production. However, the environmental benefits of 'local' are mixed. Global environmental assessments, using tools such as LCA to address the whole food chain, are increasingly needed.

<sup>92</sup> van Noordwijk, M. 2021. Agroforestry-Based Ecosystem Services: Reconciling Values of Humans and Nature in Sustainable Development. *Land* 2021, 10(7), 699; <https://doi.org/10.3390/land10070699>

<sup>93</sup> Ladha-Sabur, A., Bakalis, S., Fryer, P., Lopez-Quiroga, E. 2019. Mapping energy consumption in food manufacturing. *Trends in Food Science and Technology*. 86(270-280) <https://doi.org/10.1016/j.tifs.2019.02.034>

<sup>94</sup> Huang, H., Wie, S., Lu, J., Shyu, Y., Wang, C. 2016. Current status and future trends of high pressure processing in food industry. *Food Control* 72(1-8) <https://doi.org/10.1016/j.foodcont.2016.07.019>

<sup>95</sup> Laroque, D., Seo, S., Valencia, A., Laurindo, J., Carcifi, B. 2022. Cold plasma in food processing: Design, mechanisms, and application. *Journal of Food Engineering*. 312. <https://doi.org/10.1016/j.jfoodeng.110748>

<sup>96</sup> Leong, S. and I. Oey. 2019. Pulsed electric fields processing of plant-based foods: An overview. *Encyclopedia of Food Chemistry*. 245- 254. <https://doi.org/10.1016/B978-0-08-100596-5.21653-3>

<sup>97</sup> Bhargava, N., Kumar, K., Sharanagat. 2021. Advances in application of ultrasound in food processing, A review. *Ultrasonics Sonochemistry*. 70. <https://doi.org/10.1016/j.ultsonch.2020.105293>

<sup>98</sup> Tang, T. 2015. Unlocking potentials of microwaves for foods safety and quality. *Journal of Food Science*. 80(8) E1776-E1793. <https://doi.org/10.1111/1750-3841.12959>

### 3.4.5. Food storage

Food handling constitutes a large sector of energy consumption in producing food (*Fig. 1.7. and 1.8.*). This part of the system includes retail, restaurants, packaging, and consumers. In addition, various systems along the food value chain are involved in food storage, thus requiring significant energy. With many crops, on-farm storage is required in order to preserve product quality. The development of efficient and cost-effective solar drying with thermal energy storage systems, to continuously dry agricultural food products, is a viable substitute for fossil fuel in much of the developing world<sup>99</sup> as well as developed world.

The food and beverage sector is a leading source of cooling demand for industrial and transport refrigeration. Producers use refrigeration within the manufacturing process to safely store food products. In developing countries, the lack of refrigerated storage means that postharvest losses may be large. It also means that farmers must sell their products quickly, at market rates. During supply gluts, the inability to store products can have a detrimental effect on farmers' incomes. A start-up based in India has developed a portable cold storage box which runs on solar power, rather than the grid, and is thus unaffected by unreliable power supply. It is also portable, allowing a farmer to rent it to another farmer when it is not in use. At the other end of the spectrum, the largest food manufacturers in the world use high amounts of refrigeration and have typically relied on the use of fossil energy with HFCs (Hydrofluorocarbons) as the refrigerant, which amounts to 20% of total global HFC use. HFCs are a potent GHG<sup>100</sup>.

Refrigerated storage can account for up to 10% of the total carbon footprint for some food products when taking into account electricity inputs, the manufacturing of cooling equipment, and GHG emissions from lost refrigerants. A number of approaches can thus be put in place to reduce energy consumption and GHG emissions by: increasing energy efficiency, adding thermal insulation to the storage structure; installing/replacing energy inefficient equipment; eliminating the use of HFCs; and utilising low-carbon electricity, when possible.

## 3.5. Technology for resource optimisation

### 3.5.1. Circular food systems

The goal is to design out waste, keep materials in use and in circulation, and regenerate natural systems within the FAS. The concept of circularity originates from industrial ecology, which aims to reduce resource consumption and emissions to the environment by closing the loop of materials and substances and thus address environmental goals for sustainable development<sup>101, 102, 103</sup>. Under this paradigm, losses of materials and substances should be prevented, and otherwise be recovered for reuse, remanufacturing, and recycling. In line with these principles, moving towards a circular food system implies searching for practices and technology in food production and consumption that minimise the input of finite resources, encourage the use of regenerative ones, prevent the leakage of natural resources (e.g. carbon (C), nitrogen (N), phosphorus (P), water) from the food system, and stimulate the reuse and recycling of inevitable resource losses in a way that adds the highest possible value to the food system<sup>104</sup>.

<sup>99</sup> Bal, L., Satya, S., Naik, S. 2010. Solar dryer with thermal energy storage systems for drying agricultural food products: A review. *Renewable and sustainable energy reviews*. 14(8): 2298-2314.

<sup>100</sup> The Economist. 2019. The Cooling Imperative Forecasting the size and source of future cooling demand. A Report of The Economist Intelligence Unit. [www.eiu.com/graphics/marketing/pdf/TheCoolingimpewitative2019.pdf](http://www.eiu.com/graphics/marketing/pdf/TheCoolingimpewitative2019.pdf).

<sup>101</sup> Babbitt, C., Neff, R., Roe, B., Siddiqui, S., Chavis, C., Trabold, T. 2022. Transforming wasted food will require systemic and sustainable infrastructure innovations. *Current Opinion in Environmental Sustainability*. 54: 101151. <https://doi.org/10.1016/j.cosust.2022.101151>.

<sup>102</sup> Schneider, P., Rochell, V., Plat, K., Jaroski, A. 2021. Circular approaches in small-scale food production. *Circular Economy and Sustainability*. 1:1231-1255. <https://doi.org/10.1007/s43615-021-00129-7>

<sup>103</sup> ASABE (Resource). 2021. Transforming food and agriculture to circular systems. Special Issue. 28: 2. March/April. [www.asabe.org/Resources](http://www.asabe.org/Resources).

<sup>104</sup> De Boer, I.J.M. and M.K. van Ittersum, 2018. Circularity in agricultural production. Mansholt lecture, 19 September 2018, Brussels, Wageningen University & Research, 35 pp. [www.wacasa.wur.nl](http://www.wacasa.wur.nl)

In thinking circular food systems through, De Boer and Van Ittersum (2018) defined four principles for them. These are summarised below.

- Plant biomass is the basic building block of food and should be used by humans first.
- Food and resource losses and waste should be avoided.
- By-products from food production, processing and consumption should be recycled back into the food system.
- Animals should be used for what they are good at (for grassland that cannot be used for other food production).

Fundamentally, the concept of circular food systems has been applied and described also by such terms as ‘industrial ecology’ or ‘industrial symbiosis’, meaning that residues (waste) from an entity (business) would become input sources to another, thereby keeping materials in use. An interesting application of the concept in the FAS would be a ‘Food-Industrial Park’.

### 3.5.2. Recirculating aquaculture systems

Fish, including finfish and shellfish, contribute about 17% of global animal-based protein for human consumption and particularly so in developing countries which consume more than 75% while producing over 80% of the global fish supply<sup>105</sup>. A major concern is that the annual number of fish caught in the wild, particularly in oceans, has been stagnating since the 1990's. As the consumption of fish has been growing in the world, aquaculture (fish farming) has developed and almost half of the fish consumed derives from it. Aquaculture production needs are estimated to double from approximately 67 million tonnes (MT) in 2012 to about 140 MT in 2050<sup>106</sup>.

Aquaculture, as described above, is primarily based on confined operations in a water environment, whether marine, e.g. ‘cages’ in the oceans (along coasts predominately), or freshwater indoor and outdoor ponds on land, *Fig. 1.15.* Over the past several decades, the concept of a recirculating indoor aquaculture system (RAS) has emerged as an alternative system offering the advantages of greatly reducing land use and water requirements compared to ponds. Simply put, water is filtered from the growing tanks (confined environment) and recycled for reuse in tanks. The RAS has been performing well relative to measures of productivity and environmental parameters. A comprehensive treatment of recirculating aquaculture systems is provided by Timmons et al. (2018). Challenges persist because of high capital costs, feed sources, concern about fish diseases, food safety, and consumer acceptance. Consumers are concerned that farmed fish tend to have lower levels of omega-3 fatty acids than wild fish (World Resources, 2019). The highly intensive growing environment has also limited acceptance.

Aquaponics can be an added element to a RAS as it combines plants and fish. In an aquaponics system, fish provide waste that effectively fertilises plants, thereby approaching a closed loop system contributing to the circular economy<sup>107</sup>. Plants act essentially as filters, taking out nitrates in the system. The benefits are that little waste is produced from the overall system and inputs are minimised.

Clearly the expected increasing consumer interest in seafoods requires to foster aquaculture generally and RAS specifically. Thus, efforts to intensify aquaculture production by RAS need to be directed at approaches that mitigate the negative issues of RAS.

<sup>105</sup> OECD-FAO. 2017. Meat-Agricultural Outlook 2018-2027. Chapter 6. [www.fao.org/3/i9166e/i9166e\\_chapter6\\_meat.pdf](http://www.fao.org/3/i9166e/i9166e_chapter6_meat.pdf).

<sup>106</sup> World Resources Institute. 2019. Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2025. Final report. July 2019; Chapter 23 [https://research.wri.org/sites/default/files/2019-07WRR\\_Food\\_Full\\_Report\\_O.pdf](https://research.wri.org/sites/default/files/2019-07WRR_Food_Full_Report_O.pdf)

<sup>107</sup> Timmons, M., Guerdat, T., Vinci, B. 2018. Recirculating Aquaculture, 4th edition. Ithaca Publishing Company, LLC. ISBN 978-0971264670



**Fig. 1.15.** Indoor recirculating aquaculture system

### 3.5.3. Integrating Food, Energy and Water Systems (FEWS)

Water is required to produce food, energy is needed to provide water sources, and this interdependence has been termed the Food, Energy, Water Systems Nexus (FEWS). The agricultural sector (irrigation, livestock and aquaculture) is by far the biggest user of water in the world accounting for 70% of the global total water withdrawal. 19% of the world's cultivated land is irrigated, accounting for 300 million hectares, which accounts for almost half of the value of global crop production. In Africa and Asia, 85-90% of all the freshwater is used for agriculture<sup>108</sup>. To satisfy global demand for food, agriculture is expected to increase its water requirements by 2025 by 1.2 times.

Irrigated agriculture plays a major role in the livelihoods of nations all over the world. Although it is one of the oldest known agricultural techniques, improvements are still being made in irrigation methods and practices. During the last four decades, irrigation systems in the world have seen major improvements in technology development. Irrigation has increased by 81 percent from about 153 Mha in 1966; however, the expansion of irrigation might not be as extensive in the next 40 years owing to pressure on water resources due to climate change. Thus, innovative water saving practices are important in the face of predicted water shortages.

Also important is the need to address the water footprint within the agriculture sector. The water footprint of animal products is larger than that of crop products with equivalent nutritional value (*Table 1.1.*). The average water footprint per calorie for beef is about 20 times larger than for cereals and starchy roots. The water footprint per gram of protein for milk, eggs and chicken meat is 1.5 times larger than for pulses<sup>109</sup>. The unfavourable feed conversion efficiency for animal products is largely responsible for the relatively large water footprint of animal products. Their study shows that from a freshwater perspective, animal products from grazing systems have a smaller water footprint than products from industrial animal systems; it is yet more water-efficient to obtain calories, protein, and fat through crop products than animal ones. In addition, water savings need to be addressed at every stage of the food chain from production through consumption.

<sup>108</sup> Foley, J., Ramankutty, N., Balzer, C., Bennett, E., Brauman, K., Carpenter, S., Cassidy, E., Gerber, J., Hill, J., Johnston, M., Monfreda, C., Mueller, N. O'Connell, C., Polasky, S., Ray, D., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., West, P. and D. P. M. Zaks. 2011. Solutions for a cultivated planet. *Nature* 478(7369): 337-342..

<sup>109</sup> Mekonnen, M. and Hoekstra, A. 2012. A Global Assessment of the Water Footprint of Farm Animal Products. *Ecosystems* 15: 401-415 DOI: 10.1007/s10021-011-9517-8

Food item	Water footprint per ton (m <sup>3</sup> /ton)				Nutritional content			Water footprint per unit of nutritional value		
	Green	Blue	Grey	Total	Calorie (kcal/kg)	Protein (g/kg)	Fat (g/kg)	Calorie (liter/kcal)	Protein (liter/g protein)	Fat (liter/g fat)
Sugar crops	130	52	15	197	285	0.0	0.0	0.69	0.0	0.0
Vegetables	194	43	85	322	240	12	2.1	1.34	26	154
Starchy roots	327	16	43	387	827	13	1.7	0.47	31	226
Fruits	726	147	89	962	460	5.3	2.8	2.09	180	348
Cereals	1,232	228	184	1,644	3,208	80	15	0.51	21	112
Oil crops	2,023	220	121	2,364	2,908	146	209	0.81	16	11
Pulses	3,180	141	734	4,055	3,412	215	23	1.19	19	180
Nuts	7,016	1367	680	9,063	2,500	65	193	3.63	139	47
Milk	863	86	72	1,020	560	33	31	1.82	31	33
Eggs	2,592	244	429	3,265	1,425	111	100	2.29	29	33
Chicken meat	3,545	313	467	4,325	1,440	127	100	3.00	34	43
Butter	4,695	465	393	5,553	7,692	0.0	872	0.72	0.0	6.4
Pig meat	4,907	459	622	5,988	2,786	105	259	2.15	57	23
Sheep/goat meat	8,253	457	53	8,763	2,059	139	163	4.25	63	54
Beef	14,414	550	451	15,415	1,513	138	101	10.19	112	153

**Table 1.1.** The water Footprint of some selected food products from vegetable and animal origin (Mekonnen and Hoekstra, 2012).

**Source:** Mekonnen and Hoekstra, A Global Assessment of the Water Footprint of Farm Animal Products, Ecosystems (2012), page 409.

<https://www.waterfootprint.org/media/downloads/Mekonnen-Hoekstra-2012-WaterFootprintFarmAnimalProducts.pdf>

### 3.5.4. Improving energy consumption through technology

The use of energy in agriculture has allowed farms to create food; yet such energy use tremendously varies across the agriculture and food system. *World Energy Balances*<sup>110</sup> provides comprehensive data on energy balances for all the world's largest energy producing and consuming countries. It contains detailed data on energy supply and consumption for over 155 countries, economies, and territories, including all OECD countries, and more than 100 other key energy producing and consuming countries, as well as 35 various regional aggregates and world totals. As a first priority, the focus across the food value chain needs to be on energy conservation and efficiency to reduce its consumption as it directly and indirectly drives decarbonisation.

As the rest of the global economy, the agri-food sector is gradually reducing its dependence on fossil energy, the total renewable energy contribution being about 6% (a nuclear energy contribution of 8% is excluded from the renewable pool). Current commercial biofuels conversion processes are classified as 1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> generation technologies because of a strong reliance on food crops as seen in *Table 1.2*. Traditionally, bioethanol is produced from edible carbohydrates via a number of pre-treatment steps prior to enzymatic fermentation and product purification steps. This is the case with corn-to-ethanol and sugarcane-to-ethanol, and a typical ethanol biorefinery is in *Fig. 1.8*. It should be noted that a significant byproduct from the biorefinery is dry distillers' grains which is a valuable livestock feed.

Biorefinery technology	Type of biomass feedstock
<b>1<sup>st</sup> generation</b>	Edible crops (sunflower, sugarcane, corn, soybeans, palm, rapeseed, etc.)
<b>2<sup>nd</sup> generation</b>	Agro-residues (lignocellulosic)
<b>3<sup>rd</sup> generation</b>	Algae
<b>4<sup>th</sup> generation</b>	Non-edible plants (jatropha, soapnut, rubber seed, candlenut, etc.), food waste.

**Table 1.2.** Classification of biorefinery technology according to biomass feedstock

In addition, the agricultural sector has developed strong links with renewable energy sources<sup>111</sup>: bio-renewables constitute about 47% while the balance is ascribed to wind, geothermal, hydro, and solar facilities.

<sup>110</sup> IEA (2021), *World Energy Balances: Overview*, IEA, Paris <https://www.iea.org/reports/world-energy-balances-overview>

<sup>111</sup> IRENA and FAO. 2021. Renewable energy for agri-food systems - Towards the sustainable development goals and the Paris agreement. Abu Dhabi and Rome. <https://doi.org/10.4060/cb7433en>

Hydroelectricity features prominently in the renewable energy supply to FAS either through the National grids or off-grid situations (in rural locations where small dams on rivers provide both power and water for irrigation).

The use of locally available renewable energy sources, together with energy-efficient technologies, has become increasingly attractive to minimise impacts of rising energy costs on agri-food profitability, competitiveness, and climate effects. The contribution of different types of renewable energy sources to the overall renewable consumption by the FAS depends on the national policies for renewable energy. In the United States of America for example, there has been a steady increase in the number of agricultural operations with on-farm renewable energy producing systems (wind turbines, small hydropower, solar panels, methane digesters, biodiesel, bioethanol, etc.) over the past decade (2012-present) with solar panels as a leading source. Results of a 2021 survey report that 37% of British farmers are using renewable energy and that 35% plan to invest in renewable energy generation<sup>112</sup>.

### 3.5.4.1. Bioenergy

Bioenergy mobilisation varies greatly by country, both in terms of relative importance and by source of energy, and may be a key in some countries. At the global level, forestry products such as wood fuel (solid biofuel), charcoal, wood chips and pellets contribute about 85% of all the biomass utilised for energy purposes while agriculture accounts for about 10% of the global biomass supply (World Bioenergy Report, 2020)<sup>113</sup>. Consequently, agriculture is a key sector for increasing biomass contribution and the potential for bioenergy utilisation. The principal agricultural feedstocks include crop residues such as rice husks and wheat straw as well as biofuel crops exemplified by palm oil, sugarcane, oilseeds, etc. The role of bioenergy in the FAS is especially prominent in Africa and the developing world where a small-scale operation is the predominant mode of agricultural practice and food production. For example, gari, a common staple in the West Africa subregion, is produced from cassava fermentation<sup>114</sup> from which the resulting wet solid obtained after slurry filtration is dried and slowly roasted to taste in large open metal bowls over wood fuel-fed clay furnaces.

For cooking and other food preparation processes, biomass burning is the principal source of energy provision in developing countries. Pakistan, for example, utilises 86% of the nation's total biomass energy in the household sector<sup>115</sup> while the estimate for Nigeria is 96%<sup>116</sup>. In fact, about 80% of Nigerians in rural and urban areas depend on biomass combustion for food processing needs. Although this estimate is not representative of the entire continent, the associated detrimental effect is significant at the regional level because Nigeria's population (about 215 million) is about 20% of a continent that includes the Sahara Desert (9.2 million square kilometres). In practice, wood fuel burning results in considerable deforestation which exacerbates global GHG emissions, directly and indirectly through changing land use. Conceivably, periodic droughts particularly in Somaliland (located in the Horn of Africa), may be attributed to the local practice of felling trees for wood fuel, which not only aggravates the food-energy demand for cultivated land but also has deleterious effects on climate change through reduction in CO<sub>2</sub> sequestration and the release of CO<sub>2</sub> due to combustion. In advanced economies, however, biomass (commercial crop residues, energy crops, wood waste, black liquor, municipal solid waste, etc.) is often converted to liquid and gaseous fuels (biofuels – biodiesel and bioethanol- and biogas respectively) for transportation fuels, in heating systems, and in electricity generation. In Australia, about 1.4% of the total electricity production (3 164 GWh) is attributed to bioenergy in 2020<sup>117</sup>.

Although natural gas (essentially methane) is presently cheaper than biogas, the latter could be a renewable replacement if properly treated and may therefore be an addition to the portfolio of low-carbon technologies in the FAS. The ambitions of the EU to greatly reduce its reliance on Russian fossil fuels encourages interest and

<sup>112</sup> NFU (National Farmers' Union). 2021. Farmers prioritising sustainability investments, NFU survey shows. <https://www.nfuonline.com/media-centre/releases/farmers-prioritising-sustainability>

<sup>113</sup> World Bioenergy Association Report. 2020, Chapter 6. <https://www.worldbioenergy.org/uploads/210331%20WBA%20Annual%20Report%202020%20Public%20Version.pdf>

<sup>114</sup> Ofuya CO, Adesina AA, & Ukpong E., 1990. Characterization of the solid-state fermentation of cassava, World J. Microbiol. & Biotech., 6, 422-424. doi: 10.1007/BF01202126.

<sup>115</sup> Saeed MA, Irshad A, Sattar H, Andrews GE, Phylaktou HN & Gibbs BM, "Agricultural Waste Biomass Energy Potential in Pakistan", In: International Bioenergy (Shanghai) Exhibition and Asian Bioenergy Conference, 21-23 October 2015, Shanghai, People's Republic of China.

<sup>116</sup> Olanrewaju, F.O., Andrews, G.E., Li, H., Phylaktou, H.N., 2019. Bioenergy potential in Nigeria, Chem. Eng. Transactions, 74, 61-66.

<sup>117</sup> Clean Energy Council. 2020. Bioenergy.

expansion for biomethane. The production of renewable natural gas (RNG) from biogas upgrade using different technologies (e.g., amine scrubbing, membrane separation, pressure-swing adsorption, and water-wash) is one such approach on large agricultural farms (dairy and swine farms) in the USA. RNG is readily used for heating, cooking and as vehicle fuel<sup>118</sup>. The techno-economic assessment of RNG is favourable under the existing California environmental policy framework. Technologies for the conversion of RNG to high value-added green fuels such as biomethanol and biohydrogen are also improving the energy economics of the agri-food chain<sup>119</sup>.

Globally, biogas development is still relatively limited for various reasons including inadequate information about biogas possibilities, the cheaper cost of natural gas (fossil resource), high capital costs of current commercial biogas plants, and lack of national and local government policies to support biogas programs, as well as policies which are barriers to adoption. As a result, there is very little global data on the current installed capacity of biogas plants except for Germany and the USA. India and China are acknowledged leaders in biogas production with estimates of 4.5 million m<sup>3</sup> and 40 million m<sup>3</sup> plants respectively for heating water, cooking, and lighting. The World Bioenergy Association estimated an annual global biogas production of 30-40 billion m<sup>3</sup> (equivalent to 1080-1440 PJ e.g., 300-400 TWh). It is therefore apparent that biogas from the FAS if fully utilised, could supply about 6% of current global primary energy needs, even if, when burning, biogas produces CO<sub>2</sub>.

An intriguing utilisation of biomass (animal manure, other forms of organic waste such as slaughterhouse waste, crop biomass and crop residues) is the generation of bioenergy that has led to the creation of bioenergy villages in Germany<sup>120</sup>. In Germany alone, there are more than 50 bioenergy villages with numerous additional ones at the planning or implementation stage. An anaerobic digester is designed to convert local biomass (organic materials) to biogas to operate a combined heat and power (CHP) unit (usually an internal combustion engine connected to an electric generator) to provide heat and electricity. Heat is provided to village homes by an underground pipe loop thereby forming a district heating approach. Where waste heat from the CHP unit is inadequate to meet the heating needs of the village (largely during winters), woody biomass is burned in a furnace to provide the necessary hot fluid (water) to supplement heat available from the CHP unit. Although highly site specific, the concept of the bioenergy village can potentially offer an opportunity for the “decarbonisation” of rural areas and support sustainability.

### 3.5.4.2. Biofuels

Biofuels consisting mainly of biodiesel and bioethanol (although other bio-alcohols in the C<sub>1</sub> to C<sub>4</sub> class are also produced in relatively small quantities) are produced from plants, animal waste and algae via various transformation processes. In view of its biological origin, the global production of biofuels may be attributed to FAS (95% of global bioethanol is from agricultural products). *Fig. 1.16.* shows the production trend within the past two decades.

The top 5 leading producers of liquid biofuels are the USA, Brazil, Indonesia, Germany, and China. Additionally, both the USA (52,6 billion litres) and Brazil (30,01 billion litres) produced about 84% of the global bioethanol output as shown in *Fig. 1.17.* Corn is the principal feedstock used for bioethanol production in the USA, sugarcane is the key input in Brazil. Typical commercial plants employ 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> generation technologies (see definitions in *Table 1.2.*). The food vs. energy crop debate has however encouraged the development of 2<sup>nd</sup> generation technologies and beyond generation technologies that rely on non-edible biomass resources. In general, bioethanol is used as a transportation fuel (blended with gasoline as E10 and E85 variants in the USA), for powering fuel cells and in the manufacture of biodiesel. Thus, both bioethanol and biodiesel are utilised for vehicular operation (tractors, harvesters, freight trucks, etc.) in the FAS and in other sectors.

<sup>118</sup> Chemical Engineering Progress. 2021. Special section: Renewable natural gas. September 2021 issue. [www.aiche.org/cep](http://www.aiche.org/cep)

<sup>119</sup> Biofuels Digest. 2022. WasteFuel launches to turn agriculture waste into green fuel. Biofuels Digest <https://www.biofuelsdigest.com/bdigest/2022/02/13/wastefuel-agriculture-launches-to-turn-agriculture-waste-into-green-fuel/>

<sup>120</sup> Jenssen, T., König, A., and Eltrop, E. (2014) Bioenergy villages in Germany: Bringing a low carbon energy supply for rural areas into practice. *Renewable Energy* 61:74-80.

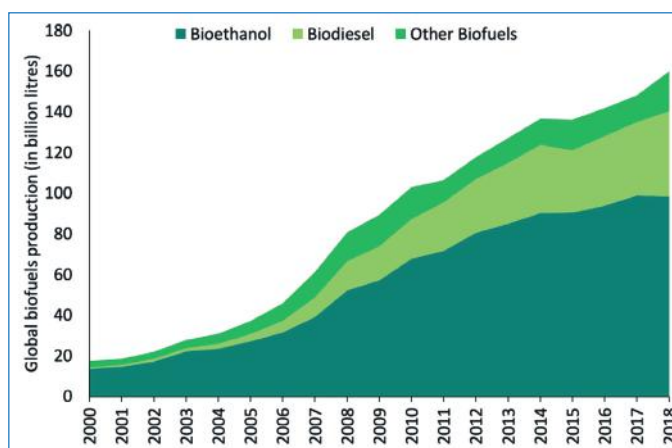


Fig. 1.16. Global production history for liquid biofuels (Chemical Engineering Progress, 2021)<sup>118</sup>

Source: Global Bioenergy Statistics 2020 produced by World Bioenergy Association, Chapter 6, p49, Figure 58.

Reference: <https://www.iea.org/data-and-statistics>

<https://www.worldbioenergy.org/uploads/201210%20WBA%20GBS%202020.pdf>

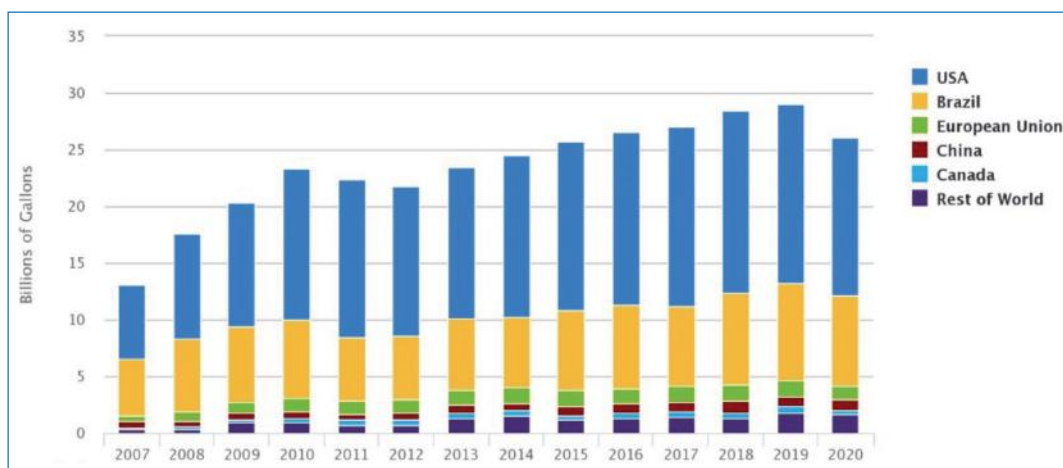


Fig. 1.17. Trends in bioethanol production for selected countries/regions

Source: "Global Ethanol Production by Country or Region" 2021. U.S. Department of Energy, Alternative Fuels Data Center. Last updated June 2021, Accessed November 7, 2022.

<https://afdc.energy.gov/data/10331>

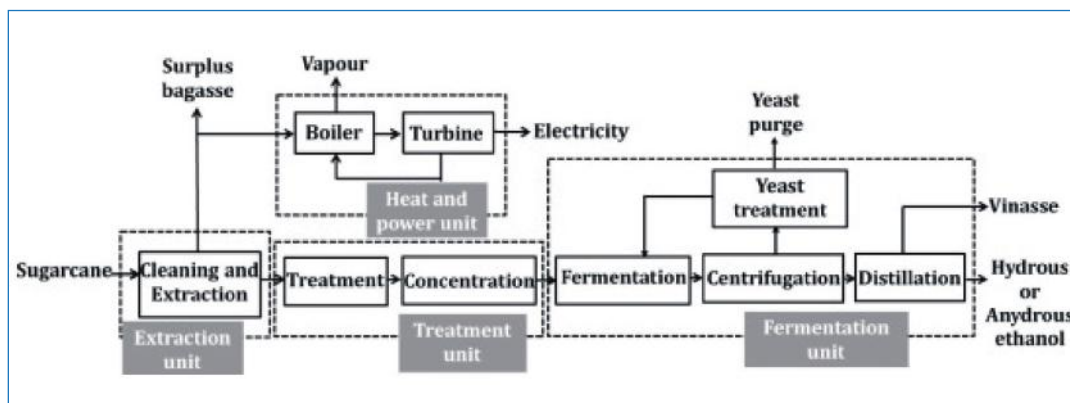


Fig. 1.18. Block diagram of a Brazilian ethanol production facility

Source: Assessing the Performance of Industrial Ethanol Fermentation Unit Using Neural Networks

<https://www.sciencedirect.com/science/article/pii/B9780444642356500322>

In recognition of the energy-food security debate and the many controversies about the relevance and opportunity to produce and promote biofuel when considering the competition with food production, recent technological developments related to the production of bioenergy from non-food sources include conversion processes for cellulosic and algae-biomass as well as non-edible and spent vegetable oils. These transformation routes include low- (enzymatic) and high-gasification, pyrolysis, hydrothermal liquefaction, temperature deconstruction. These new processes are part of a portfolio of advanced bioenergy technologies promoting investment in the food-energy-water nexus for new frontiers in sustainable development.

Advanced bioethanol processes employ various techniques including the utilisation of novel biomass sources through to integrated biorefineries that produce additional high value-added products (oxygenates, organic acids, etc.) as alternatives to conventional petrochemical derivatives, thereby helping reduce greenhouse gas emissions. Specifically, novel biomass sources include (i) novel biomass sources such as the organic fraction of municipal solid waste and some industrial residues from the paper, food, and beverage production facilities; (ii) the incorporation of new pre-treatment methods for the fractionation and conversion of lignocellulosic materials e.g., bio-extrusion and novel ionic liquids; and (iii) the utilisation of new enzyme systems and microbial strains during saccharification and fermentation processes. Furthermore, employment of non-edible biomass might also reduce land competition between food and energy production and the propensity for deforestation.

In one approach, the fermentation of potato waste (spoiled potatoes and low-grade potatoes) is used to obtain bioethanol, acetone, butanol, lactic acid, and other oxygenated intermediates in order to produce biodegradable and biocompatible PLA polymers that are environmentally friendly instead of petro-based polymers. Defining the scientific and engineering aspects in terms of yeast selection, fermentation kinetics, bioreactor design (batch, fed batch and continuous operation) has been a subject for research in the past two decades<sup>121, 122</sup>. An improvement in the production of biodiesel beyond the 1<sup>st</sup> generation route (direct esterification reaction between alcohol and high molecular weight fatty acids, e.g. palmitic, oleic, linoleic, etc.) has been achieved via transesterification of non-edible oils and microalgae leading to 2<sup>nd</sup> and 3<sup>rd</sup> generation biodiesel production route<sup>123</sup> as schematically depicted in Fig. 1.19..

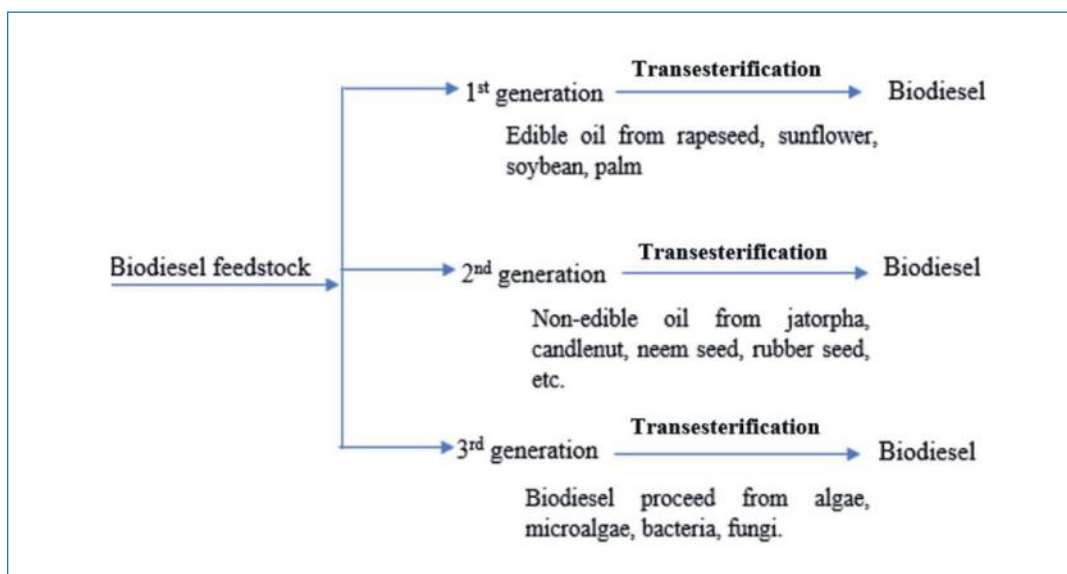


Fig. 1.19. Biodiesel production technology pathways

Source: Shaah et.al., 2021, A review on non-edible oil as a potential feedstock for biodiesel: physicochemical properties and production technologies, Page 4, Royal Society of Chemistry  
<https://pubs.rsc.org/en/content/articlehtml/2021/ra/d1ra04311k>

<sup>121</sup> Kaur, L., Singh, J., 2009. Novel Applications and Non-Food Uses of Potato: Future perspectives in nanotechnology, Special issue of Advances in Potato Chemistry & Technology, Chapter 15, 425-445. <https://www.sciencedirect.com/science/article/pii/B9780123743497000155>.

<sup>122</sup> Karapatsia, A., Penoglou G., Chatzidoukas, C., Kiparissides, C., 2015. Development of a Macroscopic Model for the Production of Bioethanol with High Yield and Productivity via the Fermentation of *Phalaris aquatica* L. Hydrolysate. Comput. Aided Chem. Eng., 37, 2129-2134, 2015.

<sup>123</sup> Shaah MAH, Hossain MS, Allafi FAS, Alsaedi A, Ismail N, Kadir MOA & Ahmad MI. 2021. A review on non-edible oil as a potential feedstock for biodiesel: physicochemical properties and production technologies, RSC Advances, 11, 25018.

Transesterification involves the tripartite reaction between alcohol, carboxylic acids and the triglycerides present in these oils to enhance biodiesel yield. Processing challenges arising from the co-product, glycerol, have been addressed by the application of an innovative process intensification design to produce biodiesel yield and purity higher than the thermodynamic limitation<sup>124</sup>. The integration of ethanol fermentation with biodiesel refinery is another advanced process development initiative to reduce overall energy consumption. It decreases separation costs, improves microbial cell recovery and reuse (with attendant fermentation at high cell densities and superior ethanol volumetric productivity, etc.).

Moreover, recent developments in the generation of electricity from agri-waste-fed microbial fuel cells (MFCs)<sup>125</sup> further strengthen confidence in this projection given that MFCs are especially adaptable for small-scale farming operations via mini-grid technologies. Thus, the current disparity in the shares of energy consumption along the agri-food chain between high and low GDP countries may be reduced. It is also evident that in addition to power generation, MFC simultaneously delivers pollutant-free, hygienic water which may be recycled for farm use. However, some significant challenges do exist in terms of high operating costs, low power output, electrode performance, possible bio-toxicity of some heavy metals, and issues of scaling up.

### 3.5.4.3. Biochar

Biochar which is obtained from the carbonisation (pyrolysis and hydrothermal treatment) of biomass (processed or unprocessed) is important for the realisation of long-term carbon sequestration along with other beneficial effects on soil fertility, water management and environmental attributes. Modern studies have shown that ancient civilisations in South America may have intentionally used *terra preta* (black earth) - a type of biochar obtained from forest burning - to enhance soil fertility for crop production<sup>126</sup>. As may be seen in Fig. 1.20., the energy produced during the process may be recycled to improve the overall efficiency of the agri-food chain. The biochar role in the FAS will experience increasing utilisation, especially in the developing world where rapid urbanisation and increased wealth with attendant growth in the agro-processing industry will lead to higher levels of organic waste, which will need to be managed in a sustainable manner. India, China, Egypt, Vietnam, Ethiopia and Cameroon have biochar production projects aimed at improving agricultural lands and climate change mitigation as illustrated in Fig. 1.21..

The USA biochar market (about 65% of the global capacity) is estimated at over USD 125 million in 2020 and is expected to increase nearly 17% (compound annual growth rate) over the next decade. Annual biochar output from the USA is about 50 000 tonnes<sup>127</sup>. The market shares for Europe, Asia and Africa are 25%, 7% and 3% respectively with consumption almost exclusively in the FAS of each region. Nevertheless, the economics of biochar production is still debatable given that pyrolysis is an energy-demanding operation. A life cycle assessment of biochar systems<sup>128</sup> analysed several biomass systems (corn stover, switchgrass, and yard waste) for net GHG emissions and economic viability and states that benefits depend on feedstock selection.

Biochar could provide moderate to large mitigation potential<sup>129</sup>. Medium evidence suggests that biochar has a technical potential of 2.6 (0.2-6.60) GtCO<sub>2e</sub>/year. However, mitigation and agronomic benefits depend strongly on the type of biochar and the properties of the soil to which it is applied.

The review of 112 scientific papers<sup>130</sup> on studies of biochar as a feed supplement to improve animal health, increase nutrient intake efficiency and thus productivity have shown mixed results. Several have pointed to a reduction in methane emissions from ruminants, others no significant change. This is therefore calling for further research.

<sup>124</sup> Chesterfield, D., Rogers, P.L., Al-Zaini, E.O., Adesina, A.A., 2012. A novel continuous extractive reactor for biodiesel production using lipolytic enzyme. *Procedia Engineering*, 49, 373-383.

<sup>125</sup> Pandit S, Savla N, Sonawane JM, Sani AM, Gupta PK, Mathuriya AS, Rai AK, Jadhav DA, Jung SP & Prasad R. 2021. Agricultural waste and wastewater as feedstock for bioelectricity generation using microbial fuel cells: Recent advances. *Fermentation*, 7, 169-202.

<sup>126</sup> Permaculture Research Institute. 2017. <https://www.permaculturenews.org/2017/08/08/terra-preta-amazon/>

<sup>127</sup> Worcester Polytechnical Institute. 2020. Biochar market profile. [https://web.wpi.edu/Pubs/E-project/Available/E-project-121019-214807/unrestricted/Biochar\\_Market\\_Profile\\_Report\\_.pdf](https://web.wpi.edu/Pubs/E-project/Available/E-project-121019-214807/unrestricted/Biochar_Market_Profile_Report_.pdf)

<sup>128</sup> Roberts, K., Gloy, B., Joseph, S., Scott, N., Lehmann, J. 2010. Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential. *Environ. Sci. Technol.* 44: 827-833. 10.1021/es902266r

<sup>129</sup> IPCC -AR6- WGIII. 2022. Chapter 7. Agriculture, Forestry and Other Land Uses.

<sup>130</sup> Schmidt H-P, Hagemann N, Draper K, Kammann C. 2019. The use of biochar in animal feeding. *PeerJ* 7:e7373 DOI 10.7717/peerj.7373

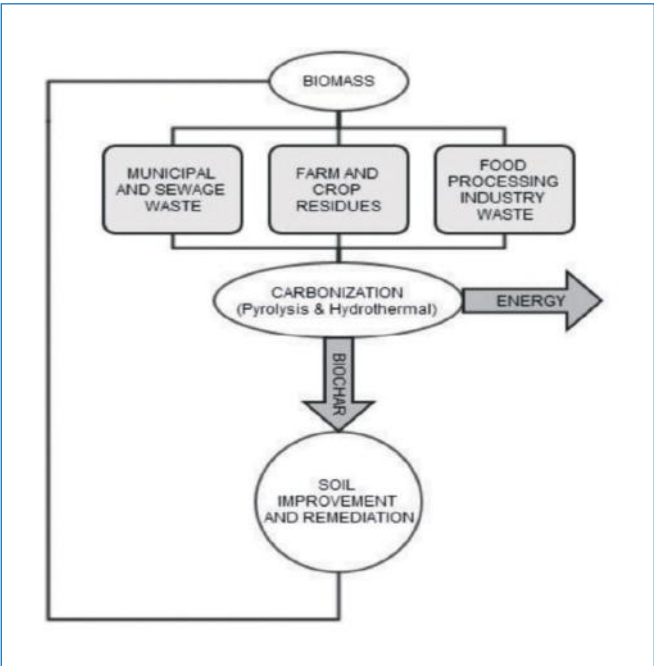


Fig. 1.20. Biochar production from the valorisation of organic waste

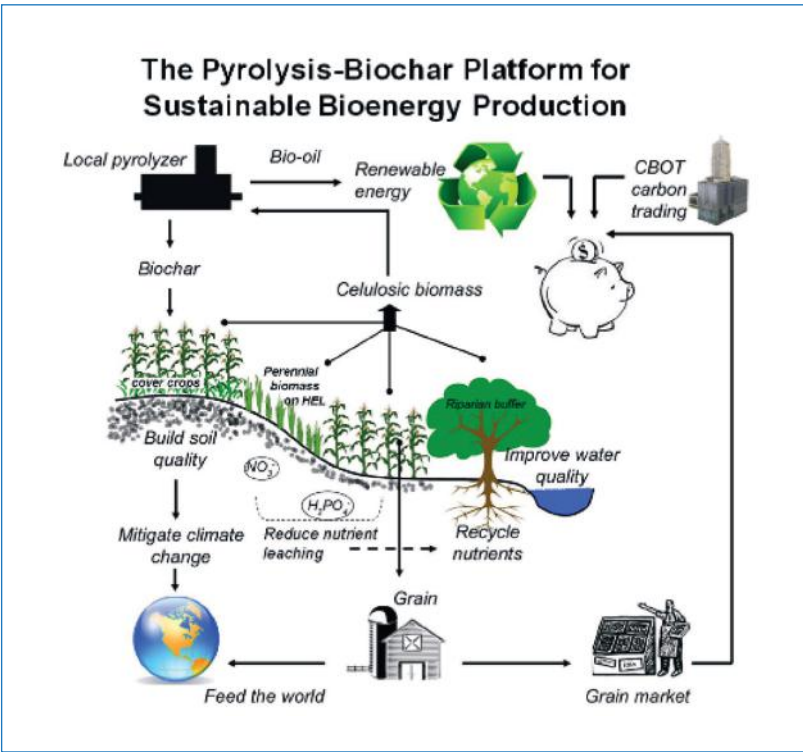


Fig. 1.21. Synergy between agriculture, energy and environment via the biochar loop (Farm Energy, 2019)<sup>131</sup>

Source: Laird, D.A., N.P. Rogovska, M. Garcia-Perez, H.P. Collins, J.D. Streubel, M. Smith. 2011. Pyrolysis and Biochar – Opportunities for Distributed Production and Soil Quality Enhancement. In: Ross Braun, Douglas L. Karlen, and Dewayne Johnson (editors) Sustainable Alternative Fuel Feedstock Opportunities, Challenges and Roadmaps for Six U.S. Regions. Proceedings of the Sustainable Feedstocks for Advanced Biofuel Workshop. SWCS publisher.

<sup>131</sup> Farm Energy, 2019, The Pyrolysis-Bioenergy-Biochar Pathway to Carbon-Negative Energy, May 31, 2019, Page 5  
<https://gcep.stanford.edu/pdfs/TechReports2018-2019/2.7.2%20GCEP%20Laird%20final%20report%205-31-19.pdf>

### 3.5.4.4. Solar energy and the co-location opportunity

The challenges of meeting the needs of food, energy, and water (frequently called a nexus) in the face of climate change have stimulated some innovative novel systems to co-locate agriculture and solar photovoltaics (PV), termed ‘agrivoltaics’ (Fig. 1.22.). The concept originally suggested by Goetzberger and Zastrow (1982)<sup>132</sup> has been further developed and analyzed by Adeh et al. (2019)<sup>133</sup>, Baron-Gifford et al. (2019)<sup>134</sup>, Dinesh et al. (2018)<sup>135</sup>, Dupraz et al. (2011)<sup>136</sup>. At present, solar PV is being employed by large utility-grid systems and on rooftops but the opportunity to develop an integrated system coupling the application of PV and crop production on the same land maximises land use without sacrificing crop land. In fact, a study of co-location in drylands has shown synergistic benefits. The shading created by the PV panels reduces heat stress on plants, which will improve yield, while transpiration from plants reduces the temperature of panels improving energy production. The development of enhanced semi-transparent PV panels would further support the co-location of PV panels and crop land.

In this perspective, one approach is to elevate solar PV panels (‘on stilts’) to allow animals and equipment to move beneath the panels; another option could be ground mounted PV panels separated by an area between panels for farming<sup>135</sup>. At this point, the number of crops which have been evaluated under PV panels is limited. Moreover, the impact of PV panels on the microclimate of air temperature, wind speed and relative humidity needs significant study to assess plant response. Some studies have shown benefits for crops like tomatoes, and lettuce<sup>133</sup>. Solar farms that have been monitored regularly by ecologists in the UK have demonstrated an increase over time in the abundance and variety of plants, pollinators, birds, and other wildlife<sup>137</sup>.

Another unique example would be co-location of solar PV panels installed over irrigation canals and reservoirs; this was suggested as an experiment in California to obtain the benefit of electricity while simultaneously reducing the evaporation from the typically uncovered water surface<sup>138</sup>. Other examples exist with installations in India and proposed applications in France.



**Fig. 1.22.** Illustration of co-location of solar PV panels and agricultural land with cropping

**Source:** Kirk Siegler/NPR, November 14, 2021: “This Colorado ‘solar garden’ is literally a farm under solar panels”  
<https://www.npr.org/2021/11/14/1054942590/solar-energy-colorado-garden-farm-land>

<sup>132</sup> Goetzberger, A., Zastrow, A., 1982. On the coexistence of solar-energy conversion and plant cultivation. *Int. J. of Solar Energy*. 1(1):55-69.  
<https://doi.org/10.1080/01425918208909875>

<sup>133</sup> Adeh, E., Good, S., Calaf, M., Higgins, C. 2019. Solar PV power potential is greatest over croplands. 2019.natureresearch, scientific reports. 9:1142.  
<https://doi.org/10.1038/s41598-019-47803-3>

<sup>134</sup> Baron-Gafford, G., Pavao-Zuckerman, M., Minor, R., Sutter, L., Barnett-Moreno, I., Blackett, R., Thompson, M., Dimond, K., Gerlak, A., Nabhan, G., Macknick, E. 2019. *Nature sustainability*. 2(848-855)

<sup>135</sup> Dinesh, H., Pearce, J., The potential of agrivoltaic systems. 2018. *Renewable and Energy Reviews*. 54(299-308). <https://dx.doi.org/10.1016/j.rser.2015.10.024>

<sup>136</sup> Dupraz, C., Marrou, H., Dufour, L., Nogier, A., Ferard, Y. 2011. Combining solar photovoltaic panels and food crops for optimizing land use: Toward new agrivoltaic schemes. *Renewable Energy*. 36(2725-2732). doi: 10.1016/j.renene.2011.03.005.

<sup>137</sup> Solar Energy UK. 2022. Everything under the sun : The facts about solar energy. Solar Trade Association UK. Chapter House, 22 Chapter St, London, SW1P 4NP.  
<https://solarenergyuk.org/wp-content/uploads>

<sup>138</sup> McKuin, B., Zumkehr, A., Ta, J., Bales, B., Viers, J., Pathak, T., Campbell, J. 2021. Energy and water co-benefits from covering canals with solar panels. *Nat Sustain* 4, 609–617 (2021). <https://doi.org/10.1038/s41893-021-00693-8>

#### 3.5.4.5. Wind energy and the co-location opportunity

Much has changed since the early 1900's when many farmers used wind power to pump water and generate power from relatively small windmills. Today, large wind turbines with generating capacity well above 1MW are common on agricultural land, particularly in the USA and Europe, (*Fig. 1.23.*). Like solar PV, co-location of wind turbines on agricultural land has become common. Farmers can lease land to wind developers<sup>139</sup>, own turbines to generate power for their farm, form a group of farmers or become wind developers. Many farmers have found wind turbines on their land to be an important source of income. Typically, large turbines use a half-acre or less of land, including the access road, while allowing farming operations for cropping and grazing of livestock up to the base of turbines. As one farmer has been known to say, "it is a lot easier to milk a wind turbine than cows". Another example of wind energy being used in the FAS is an installation of wind turbines and solar PV panels at a brewery in California. Increasingly, industries along the food value chain are implementing solar and wind sources to electrify their activities.



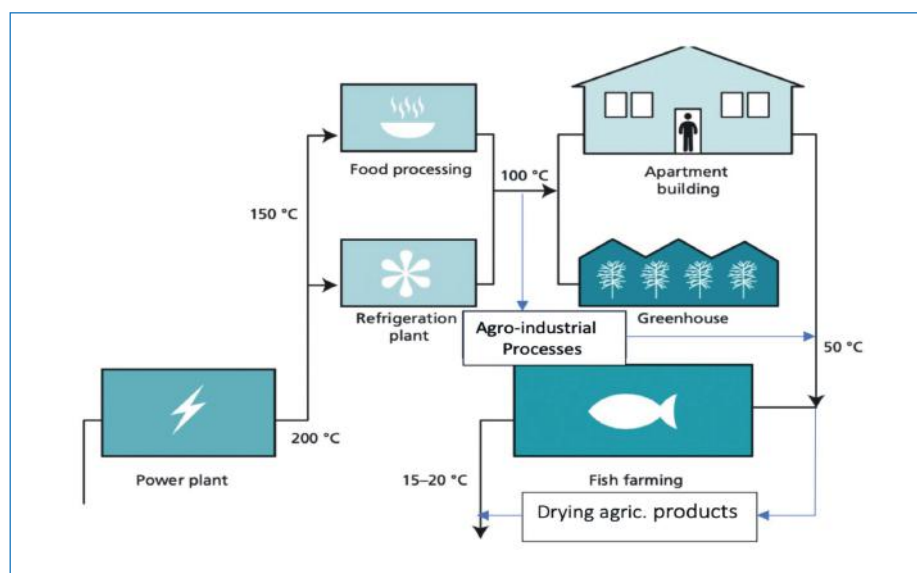
**Fig. 1.23.** Integration of large winds turbines co-located on agricultural land.  
Photo by Norman R. Scott

#### 3.5.4.6. Geothermal systems

Geothermal energy can be an attractive option if low-cost, low-enthalpy geothermal sources are available. These include geothermal resources at shallow depth, water co-produced from onshore and offshore hydrocarbon wells or already existing deep wells, and residual heat from geothermal power plants. Geothermal energy is accessible day and night every day of the year and can thus serve as a base (constant) energy source against intermittent sources. Geothermal energy is an infinite heat energy source because of the long life of radioactive isotopes (K-40, U-238, Th-232). However, the capacity of production may be restrained by limited available water. In practice, only the ground source and 'conventional' fluid-stream geothermal energy are currently used. To increase the amount of geothermal energy utilised in FAS, we need to use the available sources in multistep cascade systems as shown in *Fig. 1.24.*

Geothermal energy can be used in aquaculture, irrigation, soil heating, food/crop drying, greenhouse heating, milk pasteurisation, evaporation and distillation, refrigeration, sterilisation. The concept of cascade utilisation is an effective way to sustainably exploit the high potential of geothermal resources classified as medium and low enthalpy. In the future, the deep, dry, high temperature geothermal sources (hot dry rock, or HDR) and enhanced geothermal systems (EGS) should be increasingly utilised in multistep cascade systems in the FAS.

<sup>139</sup> NREL (National Renewable Energy Laboratory). 2022. A clear vision for wind enhancement. <https://www.nrel.gov>.



**Fig. 1.24.** Cascade use of geothermal energy illustrating applications in the FAS (adapted and modified from Lund, 2010,<sup>140</sup> Fig. 11) <https://doi.org/10.3390/en3081443>

### 3.5.4.7. Electrification and electricity on the farm

Electric vehicles are revolutionising the sector of transportation. This revolution is also taking place in agriculture, but is still at an early stage with numerous equipment manufacturers launching or working on the development of autonomous electric tractors<sup>141</sup>. Companies that manufacture tractors are investing heavily in electric tractors, which are at various stages in their development with limited availability beginning in 2022. These tractors are equipped with autonomous hardware, replete with many sensors and machine learning for data collection and tractor control. At this point, the development of the electric tractor has been focused in the 30-40 horsepower (or 25-30 kW) range, largely due to the size and weight of batteries. An advantage of smaller equipment is its potential for reduced soil compaction.

First perceptions are this high technology would be only applicable and affordable in ‘industrialized’ agriculture. Electric-driven tractors and equipment are certainly conceivable in the developing world because smaller tractors and machines are well adapted to the small land holdings. The authors envision the co-development of solar PV for charging batteries to power electric equipment. Rapid advancements in battery technologies and decreasing cost will be keys to adoption in the developing world. A unique idea of a cord-connected electric tractor (equipment) might well be an excellent way to connect solar PV to power electric equipment for the small farmer, in particular in the developing world. This approach has advantages of no battery which reduces cost and soil compaction because of reduced weight; all be it with limited range.

## 3.6. Advanced non-specific technology for FAS decarbonisation

### 3.6.1. Computing and information science: Digital Agriculture, or ‘Digital Ag’

Digital Agriculture, broadly stated, theoretically offers the possibility of benefits to both large and small producers. Digital agriculture is for instance spreading in Africa through cell phones and two main applications: advice and market prices. Yet, when it comes to embracing computer and information science through the integration of sensors, satellites, tablets, and cell phones, it is still essentially implemented by large farms. Research, teaching, and extension (outreach) programmes in Digital Agriculture have been developed in many universities around the world. Like sustainability, Digital Ag is defined or described somewhat differently by various proponents. One such description of Digital Ag is given in *Fig. 1.25.* and illustrates the linkages of innovation, discovery, and analytics with broad applications to areas throughout the food value chain of the FAS.

<sup>140</sup> Lund, J.W. 2010. Direct utilization of geothermal energy. *Energies* 3(12): 1443-1471. <https://doi.org/10.3390/en3081443>

<sup>141</sup> Future Farming. 2022. A website with continuing information frequent updates in tracking electric autonomous equipment, including tractors. <https://www.futurefarming.com>



Fig. 1.25. Use of digital technologies in agriculture

Source: Intec Open, Evolution of The Soil-Based Agriculture and Food System to Biologically-Based Indoor Systems, Norman R. Scott, Page 5

The capability of Digital Ag ultimately depends on the integration and connectivity of critical elements for a successful system, broadly categorised by Scott (2020)<sup>142</sup> as:

- **sensors** (including drones, robotics, artificial intelligence) to initiate data acquisition in the field;
- **connectivity with autonomous transfer of data** from sensors (likely many: an Internet of Things Agriculture, or IoTa) by wireless communication between digital devices, e.g. computers, tablets, and smartphones;
- **analytical devices** with software capability (machine learning, artificial intelligence, and handling of 'big' data) for storage, analysis, synthesis and the reporting of results;
- **organisations** (start-ups, consolidations, and market developments) to apply recommendations to practice in the field.

Bellon-Maurel et al. (2022)<sup>143</sup> identified four pillars that are essential for digital agriculture: (i) large data acquisition (sensors, crowd sourcing, etc.); (ii) Artificial intelligence and HPC; (iii) connections, data transfer, networks; and (iv) robotics and automation. They also highlight the importance of the institutional ecosystem (skills, innovation, start-ups, etc.) and of public policies to get the most out of the digital technology and contribute to the transition to sustainable agriculture and food systems.

### 3.6.2. Sensors

It all begins with sensors and with great advancements in sensor development; it is possible to study plant and animal physiology beyond the laboratory to measure, monitor and launch actions in plant, animal, and microbial production systems. Adding the Internet of Things to agriculture (IoTa), big data analysis, and artificial intelligence promotes a form of high-tech agriculture driven by data. Sensors and biosensors have been a major area of research and development, especially in nanoscale science and technology applications. In the section on nanotechnology, we note an extensive use of sensors in the processing, distribution and storage stages of the food value chain. Many companies in the world are actively producing an array of sensors to foster an increasing shift across the spectrum in digital agriculture, from the stage of research to that of design for use in field applications.

### 3.6.3. Robotics and automation

Robots have clearly been transferred from many industrial applications to provide a significant new technology in the FAS. Such technology has contributed to many different applications in labour-intensive crops. It has been used for example: (i) to identify weeds and implement weed control (e.g. to mechanically remove weeds, employ microwave technology to kill weeds, and other methods); (ii) to spot the onset of plant diseases or pests

<sup>142</sup> Scott, N. 2021. Evolution of the soil-based agriculture and food system to biologically-based indoor systems. In : Technology in Agriculture. Eds. Ahmed, F. and Sultan, E. London :In TechOpen. DOI: <http://dx.doi.org/10.5772/intechopen.99497>

<sup>143</sup> Bellon-Maurel V., Brossard L., Garcia F., Mitton N., Termier A., 2022. Agriculture and Digital Technology: Getting the most out of digital technology to contribute to the transition to sustainable agriculture and food systems. pp.1-198, INRIA-INRAE. <https://doi.org/10.17180/wmkb-ty56-en>

and deliver intervention schemes (e.g. for citrus greening, early potato blight, and many more); (iii) to deliver fertiliser, pesticides, and herbicides at specific sites; (iv) to spot and control spray delivery in vineyards and orchards (including pollinator applications); (v) for robotic ‘ducks’ in rice fields to control weeds without pesticides; (vi) with robots to pick fruits (e.g. apples, citrus, strawberries, raspberries and more), (vii) in robots for transplanting; (viii) in soil robots for soil testing and determining water-use effectiveness; (ix) within food processing plants, robots to size, sort and package products; and (x) within autonomous robotic vehicles (including tractors, some of which are electric) to perform field operations that could reduce soil compaction and simultaneously track data.

Robots have entered the dairy farm to milk and feed cows. Cows enter a special stall and are milked while feed is available during milking, based on milk production. Access to the milking stall is based on n times milking per day as a function of the cows’ milk production. The identity of each cow is transmitted by an electronic animal tag, and sensors within the teat cup provide data on temperature, milk conductivity, and milk quality. A highly desirable future biosensor would detect progesterone levels that could provide key data on reproductive status (estrus). A single robot station can handle about 50 cows per day, which makes the system compatible with small farms as well as large farms. The milking robot has been adopted on small farms to address such challenges as the unavailability of human labour, freedom from the daily minimum commitment of twice milking, thus permitting a normal life; and, because the cow can be milked more often, increased production has been experienced. Moreover, a few large rotating milking parlours with robotic milking units have been installed across the world.

The development and production of field and harvest robots is a global business. *Future Farming* (2022)<sup>144</sup> produced a robot catalogue identifying more than 35 field and harvest robots from sixteen countries. In this first edition, seven of the robots are manufactured in the USA and six from the Netherlands. It is anticipated that numbers will continue to increase significantly in the future.

Yet the promotion of mechanisation may raise important sustainability concerns. As stated by the Malabo-Montpellier Panel (2018)<sup>145</sup>, in the case of Africa, “with new emerging machines and technologies on the horizon, it is ever more important that governments design mechanisation strategies that generate new employment opportunities for those working in the rural on- and off-farm economies. This is particularly important given how critical employment is to reducing poverty and migration and maintaining political stability”.

#### 3.6.4. Drones and Unmanned Aerial Vehicles (UAV)

While unmanned aerial vehicles (UAV), especially drones, have been widely employed in military missions and for intelligence gathering, their use in agriculture is exploding. Relatively inexpensive and reasonably simple to operate, drones can be equipped with sensors, cameras, and specialised hardware to perform a large array of functions in agriculture. Equipped with appropriate devices, drones are: (i) used to develop high-definition maps of fields that provide an ability to create prescriptive-defined application of sprays, fertiliser, pesticides, and herbicides, (ii) used to count the number of plants, fruits and flowers to forecast yields; (iii) employed to distribute seeds for crop planting; (iv) used when equipped with multispectral, hyperspectral and thermal cameras to measure chlorophyll, crop biomass, and plant health, as well as determine ground temperature, plant numbers, soil water content, and estimate crop yields; (v) a potential way to deliver contraceptives to manage wild horse and burro population; (vi) used to monitor a plant water stress and control irrigation so as to efficiently use water; (vii) used as ‘nanobees’ (miniature drones) should normal bee pollinators be absent or of an inadequate number to supplement the pollination process; (viii) used in outdoor livestock systems to monitor animals for estrus behaviour as well as control and manage the herd; and (xi) employed to monitor and track animals in inaccessible areas in the natural environment. In some countries, such as China, they might be used to spray pesticides, while this might be prohibited in other countries.

<sup>144</sup> Future Farming. 2022. A website with continuing information frequent updates in tracking electric autonomous equipment, including tractors. <https://www.futurefarming.com>

<sup>145</sup> Malabo-Montpellier Panel. 2018. <https://www.mamopanel.org/resources/mechanization/reports-and-briefings/summary-mechanized-transforming-africas-agricultur/>

### 3.6.5. Biotechnology

The impacts of crop biotechnology have been studied over a 22-year period (1996-2018) on farm income and production<sup>146</sup> and on the environment<sup>147</sup>. Significant economic benefits at the farm level are globally estimated at USD 18.9 billion in 2018 and USD 225 billion (in nominal terms) for the 22 year-period. These gains are attributed at 52% to farmers in developing countries and 48% in developed countries with 72% of the gains based on yield and production increases and 28% from cost savings<sup>146</sup>. Returns on investment in genetically modified (GM) crop seeds were calculated at an average of USD 4.41 per dollar invested in developing countries and USD 3.24 per dollar invested in developed countries.

Assessments of environmental impact of GM crops estimate the use of global crop protection products to be reduced by 8.6% over this 22-year period. Reduced GHG emissions, through the adoption of reduced tillage, as it curtails fuel usage and improves soil carbon retention, are estimated to reduce the environmental impact by 19%. However, no-till management on croplands has become a controversial approach for storing carbon in soil due to conflicting findings<sup>148</sup>.

The annual report of the International Service for the Acquisition of Agri-biotech Applications (ISAAA) provides a yearly global update on the adoption and distribution of biotech crops<sup>149</sup>. The 2019 report shows that GM crops increased in 29 countries with 190.4 billion hectares. A total of 72 countries have adopted biotech crops, with 29 having planted crops and 43 additional countries importing biotech crops for food, feed, and processing.

The biological world in 2020 was marked by CRISPR technology receiving recognition through the Nobel Prize in Chemistry awarded to its inventors. Simply stated, CRISPR is a unique technology used to edit selected genes by finding a specific bit of DNA inside a cell and altering it. Already applied in human health, it is being used in plant science for traits that can prevent disease, create pest resistance, increase resiliency, and improve crop yields.

Animal biotechnology has greatly contributed to the increasing of livestock productivity by ramping up production, reproductive efficiency, genetic improvement, animal nutrition, and animal health<sup>150</sup>. More specifically, recombinant bovine somatotropin (rBST) has been shown to increase feed conversion and milk yield. Major advances in animal reproduction have been experienced with biotechnology applied to genetics and breeding. The U.S. Food and Drug Administration approved in December 2020 a first-of-its-kind Intentional Genomic Alteration (IGA) in domestic pigs for food or human therapeutics<sup>151</sup>.

However, as shown by the HLPE (2019, see Box 2), “despite the uptake of Genetically Modified technology, debates continue to be polarised and there are public concerns about safety, potential negative environmental impacts, resistance to corporatisation of agriculture and concerns about the ethics of gene modification”.

<sup>146</sup> Brookes, G. and Barfoot, P. 2020a. GM crop technology use 1996-2018: farm income and production impacts. *GM Crops and Foods* 11(4). <https://doi.org/10.1080/21645698.2020.1779574>

<sup>147</sup> Brookes, G., Barfoot, P. 2020b. Environmental impacts of genetically modified (GM) crop use 1996-2018: impacts on pesticide use and carbon emissions. *GM Crops and Foods*.11(4). <https://doi.org/10.1080/21645698.2020.1773198>

<sup>148</sup> Ogle, S., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F., McConkey, B., Regina, K., Vazquez-Amabile, G. 2019. Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. *Sci Rep* 9, 11665 (2019). <https://doi.org/10.1038/s41598-019-47861-7>

<sup>149</sup> ISAAA. (International Service for the Acquisition of Agri-Biotech Applications). 2020. ISAAA Brief 55-2019: Global status of biotech crops. 2020. [www.isaaa.org](http://www.isaaa.org)

<sup>150</sup> Tonamo, A., 2015. Review status of animal biotechnology and options for improving animal production in developing countries. 2015. *J. of Biology, Agriculture and Healthcare*. 5(19): 21- 31. ISSN 2225-093X

<sup>151</sup> FDA (Food and Drug Administration). 2020. Press Release December 14, 2020. Approves First-of-its-Kind Intentional Genomic Alteration in Line of Domestic Pigs for Both Human Food, Potential Therapeutic Uses

*Box 2. The controversial issue of Genetically Modified technology as an example to addressing sustainability concerns (Source: HLPE 2019)*

“There clearly needs to be more investment in agriculture and food research, including in careful assessment of modern biotechnologies, for improving food and nutritional security and delivering sustainable food systems in the wake of climate variability and change... On a global scale, the products of modern biotechnologies will be part of the transition towards Sustainable Food Systems... They are already a significant component of the agricultural systems in a number of countries... Recent calls for a global observatory for gene editing propose increased scrutiny, dialogue and deliberation on the use of modern biotechnologies...” p 80)

“Looking across the... controversial issues, it is possible to identify knowledge gaps around specific metrics of food system performance required to guide food system transitions and to clarify critical decisions that need to be made, including opportunities for reformulating the controversial issues towards the design of solutions on the one hand, or political choices among divergent views on the other” (p 18)

### 3.6.6. Nanotechnology

Nanoscale science and engineering offers the potential to significantly revolutionise the FAS. It can play an important role at each point along the FAS supply chain from production through consumption, including in the management of food losses and waste<sup>152, 153</sup>. In broad terms, nanotechnology can be a key element in the: (i) “re-engineering” of crops, animals, microbes, and other living systems at the genetic and cellular level; (ii) development of efficient, “smart” and self-replicating production technologies and inputs; (iii) development of tools and systems for identification, tracking and monitoring; and (iv) manufacture of new materials and modified crops, animals and food products.

The major part of advancement in the applications of nanotechnology in the FAS has largely occurred since 2000. Areas of application include food quality and safety, animal health monitoring and management, plant systems, environmental systems, and the assessment of societal impacts. Here are just a few applications: (i) nanomaterials for crop and animal disease detection and the detection of residues, trace chemicals, viruses, antibiotics and pathogens; (ii) the enhancement of plant nutrient uptake, nutrient use efficiency, and fertiliser efficiency by the controlled release of agrochemicals; (iii) seed coatings with nano-based chemicals to promote seed germination and deliver long-term disease and pathogen resistance; (iv) DNA-based genetic materials using DNA-based nano-barcode with a multi-probe sensor to detect pathogens (in plants, animals and environmental contaminants); (v) the enhancement of water-use efficiency in crops by improving water retention and develop ‘smart plants’ to provide information on water needs and manage irrigation; and (vi) widespread advances in food packaging and food-contact materials for quality and increased shelf life.

Against this significant list of successful developments, nanotechnology’s vision for the future is impressive<sup>154, 155, 156, 157, 158</sup> and includes among others: (i) the selectivity, robustness, ease of use, cost-effectiveness and longevity of nano-sensors as key components of the field-distributed, intelligent sensor network for monitoring and control and as part of the Internet of Agricultural Things (IoAT), (ii) the use of common field crops (e.g.,

<sup>152</sup> Scott, N., Chen, H. Nanoscale science and engineering for agriculture and food systems. 2012. *Industrial Biotechnology* 8((6): 340-343. <https://doi.org/10.1089/ind.2012.1549> (532-540) <https://doi.org/10.1038/s41565-0900439-5>

<sup>153</sup> Scott, N., Chen, H., Cui, H. 2018. Nanotechnology applications and implications of agrochemicals toward sustainable agriculture and food systems. *J. Agric. Food Chem.* 66(26): 5451-6456. DOI:10.1021/acs.jafc.8b00964

<sup>154</sup> Scott, N., Chen, H., Cui, H. 2018. Nanotechnology applications and implications of agrochemicals toward sustainable agriculture and food systems. *J. Agric. Food Chem.* 66(26): 5451-6456. DOI:10.1021/acs.jafc.8b00964; Giraldo et.al., 2019; Lew et.al., 2020; Gilbertson et.al., 2020; Kah et al., 2019.

<sup>155</sup> Giraldo, J., Wu, H., Newkirk, G. Kruss, S. 2019. Nanobiotechnology approaches for engineering smart plant sensors. *Nature Biotechnology*. 14 (541-553) <https://doi.org/10.1038/s41565-019-0470-6>

<sup>156</sup> Lew, T., Sarojam, R., Jang, I., Park, B., Naqvi, N., Wong, M., Singh, G., Ram, R., Shoseyov, O., Saito, K., Chua, N., Strano, . 2020 M. Species-independent analytical tools for next generation agriculture. *Nature Plants*. 6 (1408-1417) <https://doi.org/10.1038/s41477-020-00808-7>

<sup>157</sup> Gilbertson, L., Pourzahedi, L., Laughton, S., Gao, X., Zimmerman, J., Theis, T., Westerhoff, P. Lowry, G., 2020. Guiding the design space for nanotechnology to advance sustainable crop production. *Nature Nanotechnology*. <https://doi.org/10.1038/s41565-020-0706-5>

<sup>158</sup> Kah, M., Tufenkji, N., White, J. 2020. Nano-enabled strategies to enhance crop nutrition and protection. *Nature Nanotechnology*. 14(532-540). <https://doi.org/10.1038/s41565-019-0439-5>

corn, soybean, and grains) and trees to make sustainable chemicals; (iii) the design of nitrogen-producing microbiome and seed coatings that promote crops to produce their own nitrogen fertiliser; (iv) systems tracking the integrity of food (plant and animal) from production, transport, and storage to consumer consumption; (v) unique sensors: ingestible ones to monitor gut health, tooth sensors to measure food properties, or even chopsticks to detect food characteristics including nutrients; (vi) DNA lifelike materials from agricultural biomass, ranging from biosensors to biomanufacturing (replacing petrochemicals), to the development of value-added products including plastics that are biodegradable.

As in the case of biotechnology, some concern and socio-technical controversies have been expressed about health, environment, and social side-effects. This might be illustrated by the presence of nanoparticles in foods and their consequences for food safety. The EU has for instance banned the use of titanium dioxide in food.

### 3.6.7. Cross-cutting technology related observations

Technology played a pivotal role in the impressive agricultural transformation that took place in the 20<sup>th</sup> century and contributed to the increase and diversity of food supply despite demographic transition. Similarly, technology should play an essential role in addressing current and future sustainability challenges that bring together agriculture, food, health, energy, climate, environment, and social justice.

If technology should be considered a necessary and useful resource, there is no magic bullet, nor 'one size fits all' solution. Any technology may offer potential avenues for progress and provide benefits, but also bring about drawbacks and contribute to the emergence of new problems. In addition, the profound changes that are required will depend on a series of many complementary solutions, as no single one might address the breadth and depth of this challenge. These basic assumptions have two consequences.

They first call for the need to generate appropriate metrics and assessments that account for the capacity of technology to contribute, not only to decarbonisation, but also to all dimensions of sustainability as there might be trade-offs among them. This is neither trivial nor easy, as most assessments are context- as well as time- and space-scale specific, account for complex and uncertain processes, and require methods and indicators that are not always available. This is in particular the case for addressing emerging issues that were not considered in the past, in particular climate change.

The second consequence refers to the need for context-specific design processes. This is essential to jointly consider technological resources, the innovation process and their contributions to addressing sustainability concerns. Agricultural and food systems are context-specific. Their transformation relies on local adapted practice changes that depend on resources and available technology, know-how, risk management, etc., and may involve various stakeholders with divergent vested interests. In addition to discussions on its impact, technology implementation may thus face resistance related to values and interests, conflicts of interest, risk management and path dependency<sup>159</sup> that make it very complex to analyse its political economy.

Finally, technology may have a controversial dimension and, alongside growing suspicion concerning technology and the spread of fake news, may become a polemical and polarising issue, as the well-known and documented case for Genetically Modified Organisms shows. In order to understand and consider controversies related to agroecology, the HLPE for example identified divergent views and values regarding 6 topics that were analysed taking into consideration governance, economic, resource, social, cultural and knowledge factors.

<sup>159</sup> HLPE. 2017a. Nutrition and food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. Retrieved from <https://www.fao.org/3/i7846e/i7846e.pdf>

## 4. Different narratives

The transformation of food systems will take place considering four sets of driving and steering forces. The first set will depend upon the type of technology that is promoted and the economic model it refers to and serves. We can in particular foresee three differentiated and simultaneous trends: (i) the acceleration of technology, which is intensive in capital, adapted to large-scale production or industrial units and contributes to economies of scale; (ii) high tech development, implemented by start-ups and small and agile production units that permanently adapt to the market and constitute themselves in economic clusters; (iii) the advance of low-tech green and circular systems that favour local informal chains based on proximity and resource recycling.

The second set is related to the capacity of technology to ensure production independently from land use: it will be a key driver in the future to address environmental issues, although the energy consumption of such modalities will be key to alleviating the environment footprint.

The third set is about what we shall produce and will depend on what we will consume and waste. The share of animal source products in consumption will be key and the young generation is likely to engage and promote deep changes in consumption patterns.

The fourth set for the transformation will depend on the capacity or not to promote the co-existence of different food systems, building upon synergies and complementarities at territorial and regional levels as a way to ensure adaptability, resilience, and sustainability. This relates to agricultural production and the way land use takes into account environmental concerns through landscape symbiosis that address the artificial opposition between options represented by land sharing and land sparing (see section 4). This also relates to the agro-industrial sector with the development of territorial symbiosis or of specialised production basins.

These four sets will shape the future of food systems, and, as a consequence their contribution to decarbonisation, their performance regarding energy production and consumption and their environment footprint, including their contribution to climate change. Among plausible and possible futures, when considering the two axis of “Degradation versus sustainability” and “Regional versus global” at the global level, we could for example imagine:

- the general collapse of food systems because of their high and uniform specialisation and, as a consequence, their low resistance to shocks;
- a differentiated transformation in which sustainable production “pockets” emerge and become the regional or global cellar, while the food production capacity of other regions is completely degraded;
- a balanced organisation of sustainable food systems based on territorial symbiosis and connected to each other through efficient global regulation mechanisms;
- an archipelago of local sustainable food systems with little exchanges.

Further research is needed to prepare the methods, metrics, and equipment to assess such an evolution.

## 5. Key messages and recommendations

A large panel of technologies is available to act on the decarbonisation of food and agriculture systems (FAS). The following key messages summarise our main recommendations toward this end. Yet, because of the complex, multidimensional and interscale interactions of the FAS transformation, knowledge is still missing to steer desirable pathways.

### Key Messages

#### 5.1. Major transformations

The Food and agriculture systems (FAS) have gone through deep transformations to cope with the huge demographic transition and feed the world. Although the required increase in production has been achieved, this transformation generated sustainability concerns, which in turn call again for radical change. This need is reinforced by global changes (climate change, conflicts and wars, etc.) that will dramatically impact food, agriculture, and ecosystems around the world.

#### 5.2. Decarbonisation and methane reduction

Decarbonisation and methane reduction are essential components in this transformation but not the only ones. This implies trade-offs among diverging sustainability objectives and across time and space scales, and calls for the strengthening of our capacity to address such trade-offs through evidence and arbitration mechanisms; a nexus approach and specific mechanisms are needed to address controversies and arbitrate contradictions at all levels, including between local innovations and global challenges.

#### 5.3. Disruptive technologies and behaviour

There are now strong driving and steering forces fostering the transformation of the FAS, including calls for significant change and reduction in the consumption of animal-based foods from the young generation to a healthier diet with less meat; yet there is much controversy, in particular regarding the mobilisation of disruptive technologies because of entrenched long-standing traditional practices, together with the association of food with religious and cultural dimensions, on the one hand, and the increasing concentration in the agri-food sector on the other hand.

#### 5.4. System of systems

The FAS is a system of systems and thus systems thinking is critical to transform the FAS towards meeting sustainable development goals; *however, it is the people who will make it happen – or not*. To that end, there is need to move beyond contentious debates, acknowledge the social, cultural, economic and political dimensions of problems and solutions, and accept and design a broad array of approaches valuing scientific evidence as much as possible.

#### 5.5. Advances in science and technology including design and metrics

Science and technology were keys in generating the past transformation of the food systems and will continue to play an eminent role; yet their impact can be either negative or positive, and innovation does not always contribute to sustainable development. While, in the past, the performance criteria of both technology and innovation in the FAS mainly relied on productivity and economic competitiveness, today, addressing future challenges requires new assessment methods, criteria, and metrics; this not only applies to the agricultural production, but also to the whole food system; this is needed to promote decarbonisation and address trade-offs towards sustainability.

#### 5.6. Quantitative impact of specific technologies

There is a need to assess the potential contributions of specific technologies for decarbonisation. However, this very much depends on each specific ecological, technological and social context, on the one hand, and on the way each technology is implemented on the other hand. Such knowledge is rarely available today and this would need a strong investment in research and expertise.

**5.7. Stable Public Policies**

Stable and comprehensive public policies are needed to make sure technology and innovation contribute to decarbonisation; this includes in particular trade agreements, intellectual property rights, market regulation, taxes, and subsidies.

**5.8. Need for research and extension**

Research is required to design and transfer technology and information to all stakeholders including farmers, processors, consumers, extension/outreach persons, and policy makers at all levels of government from the global to the local. Research is also needed to foster participation and innovation arrangements to identify drivers and obstacles to innovation, and assess contributions to decarbonisation participate in innovation arrangements, identify drivers and obstacles to innovation, and assess contributions to decarbonisation.

*Recommendations***5.9. Food supply chain**

We recommend that science and technology innovations for decarbonisation receive increased emphasis for development at all stages of the FAS from pre-production inputs, through food production, processing, packaging, distribution and consumption, to waste management.

**5.10. Methane reduction**

We recommend that pathways be further developed to reduce biogenic methane from livestock and rice cultivation. New feeds, feed additives, improvements in manure management, etc. are needed to significantly reduce methane emissions from ruminant livestock. Improvements in irrigation techniques, increased efficiency in the use of fertilisers, new rice varieties and the potential use of bacteria in the field should improve, so as to address the issue of reducing the share of methane in the rice fields.

**5.11. Energy efficiency and decarbonisation**

We recommend that energy efficiency and conservation practices be top priorities along the supply chain ‘from farm to fork’, because direct and indirect energy savings drive decarbonisation. We recommend to increase developments in the co-location of solar Photovoltaics, ‘agrivoltaics’ and wind turbines on agriculture land. We also recommend electrification across the food supply chain from field equipment (tractors), food processing, storage, transportation, to consumption.

**5.12. Alternative protein foods / Controlled environment agriculture**

We recommend the application of Life Cycle Assessment studies to assess any reported environmental benefits of alternative protein foods, 3D-printed foods, aquaculture / aquaponic systems, and advanced greenhouses including vertical farms to quantify this potential transition to a healthier diet that includes less traditional meat and significant benefits for decarbonisation.

**5.13. Circular economy**

We recommend that the FAS adopt and apply the principles of circularity as a key strategy to address the reduction of food loss and waste along the food supply chain from ‘farm to fork’.

**5.14. Biomass / Bioenergy**

We recommend restricting the utilisation of biomass for bioenergy, biofuels, and biochar to situations that do not compete with land use for food crops and that do not generate price volatility and food insecurity. Furthermore, biogas produced from waste organic sources can be an important driver of combined heat and power systems at farm, community and district levels.

**5.15. Biotechnology**

We recommend the adoption of biotechnology in the FAS when improved performance also contributes to lowering GHG emissions as less fossil fuel is being used and to reducing the amount and use of disease protection products.

**5.16. Nanotechnology**

We recommend the adoption of nanotechnology when it contributes to addressing decarbonisation, examples of which include biomanufacturing to replace petroleum-based products, seed coatings to enhance nutrient uptakes, more efficient uptakes of nitrogen fertilisers that may reduce the amount of nitrogen (N) needed and curtail N losses, and the development of safe edible packaging, to only mention a few.

**5.17. Nitrogen use efficiency**

We recommend the right application of N-fertiliser use through practices that enhance nitrogen use efficiency: the right N source, right rate, right time of application, and right placement. Depending on the context, this could lead to an increase or a reduction through, for example, integrated soil management approaches, precision agriculture for placement and nanotechnology for time release.

**5.18. Regenerative agriculture / Agroecology / Agroforestry**

We recommend the initiation of in-depth studies to quantify expectations that these practices sequester soil carbon and also enhance soil health. This is important to develop public incentives and a rational and equitable carbon market for farmers.

**5.19. Digital Agriculture**

We recommend the continued assessment of decarbonisation resulting from Digital Agriculture. Digital agriculture is a marriage of seemingly disparate technologies involving advanced sensors, artificial intelligence, data integration, big data, drones, robots, nanotechnology, smart food packaging, electronic devices (computers, tablets, smartphones), tracking technologies, and climate information that lead to sustainability in food production and processing.

**5.20. Policy framework**

We recommend the development of a facilitating policy framework and the implementation of adapted and context-specific policies to fully capture the benefits of science, engineering and innovation, while ensuring reduced inequality and the coordinated governance of land and oceans so that FAS may improve and gain in sustainability.

## List of abbreviations and acronyms

---

<b>CHP</b>	Combined Heat and Power
<b>CRISPR</b>	Clustered Regularly Interspersed Short Palindromic Repeats
<b>DNA</b>	Deoxyribonucleic Acid
<b>EU</b>	European Union
<b>EGS</b>	Enhanced Geothermal Systems
<b>FAS</b>	Food and Agriculture System
<b>FLW</b>	Food Loss and Waste
<b>GM</b>	Genetically Modified
<b>GHG</b>	Greenhouse Gas
<b>HLPE/CFS</b>	High-Level Panel of Experts of the UN Committee on World Food Security
<b>HPC</b>	High Performance Computing
<b>IGA</b>	Intentional Genomic Alteration
<b>IoAT</b>	Agricultural Internet of Things
<b>IPCC</b>	International Panel on Climate Change
<b>LCA</b>	Life cycle Assessment
<b>LULUC</b>	Land use and land use change
<b>MIMO</b>	Multiple Input-Multiple Output
<b>NFU</b>	National Farmers' Union
<b>OECD</b>	Organisation for Economic Co-operation and Development
<b>NRC</b>	National Research Council
<b>PAR</b>	Photosynthetic Active Radiation
<b>RNG</b>	Renewable Natural Gas
<b>SDG</b>	Sustainable Development Goal
<b>TEA</b>	Techno-Economic Assessment
<b>UAV</b>	Unmanned Aerial Vehicles
<b>UN</b>	United Nations
<b>VF</b>	Vertical Farm

---

## CHAPTER 2. BUILDINGS AND SMART CITIES

### Members of the Working Group

**Albarrán-Núñez José Francisco**, Mexico

**Bamberger Yves**, France

**Bandyopadhyay Bibek**, India

**Bertero Raul**, Argentina

**Cataldo José**, Uruguay

**Chaturvedi Pradeep**, India (Co-chair)

**Domínguez José**, Spain

**Duic Neven**, Croatia

**Fu Lin**, China

**Godefroy Julie**, United Kingdom

**Hu Shan**, China

**Jiang Yi**, China

**Langlais Catherine**, France

**Lieuwen Timothy Charles**, United States of America

**Mesarovic Miodrag**, Serbia

**Morillón David**, Mexico

**Wagner Ulrich**, Germany (Co-chair)

**Wu Yanting**, China

## Table of Contents

---

<b>Executive Summary</b>	83
<b>1. Introduction</b>	84
1.1. Buildings' energy consumption and emissions	84
1.1.1. Current situation: global energy demand in buildings and corresponding carbon emissions	84
1.1.2. Adopted resolutions and challenges	85
1.2. Occupant behaviour, comfort and technical choices	87
<b>2. Decarbonisation of buildings' energy consumption</b>	89
2.1. Buildings' efficiency: existing and new buildings, architectural design and construction	89
2.1.1. Retrofitting of existing buildings	89
2.1.2. New buildings	91
2.1.3. Buildings with PV external surfaces as energy 'prosumers'	92
2.2. Electrification	93
2.2.1. Heating	93
2.2.2. Cooling	94
2.2.3. Domestic Hot Water	96
2.2.4. Cooking	98
2.3. Buildings' energy flexibility	100
2.4. Potential role of hydrogen in the buildings sector	102
<b>3. Decarbonisation of urban energy supply systems</b>	102
3.1. Low-carbon heating district networks	102
3.1.1. Various district heating and cooling systems	102
3.1.2. Low temperature heat sources	102
3.1.3. Seasonal heat storage	104
3.1.4. Temperature converters based on heat pumps	104
3.1.5. Long-distance heat transportation	105
3.2. Potential role of hydrogen for cities and communities	105
3.3. Smart Cities	105
3.3.1. Introduction to Smart Cities	105
3.3.2. Cities in the world: current situation	106
3.3.3. Challenges for cities to become smart	106
3.3.4. Existing, forthcoming and possible breakthrough solutions for smart cities	106
<b>4. Sustainability, public policies and regulation</b>	108
<b>5. Education and training</b>	110
5.1. Old and new needs toward low-carbon buildings	110
5.2. Higher education	111
5.3. Training the future apprentices	111
5.4. Lifelong learning – Continuous Professional Development	112

<b>6.</b>	<b>Case Studies</b>	113
6.1.	Buildings' decarbonisation in Latin-America and impacts on regulation	113
6.2.	Decarbonisation at the district level: the case of poor neighbourhoods in developing countries	115
6.3.	Two case studies of district heat networks in China	119
<b>7.</b>	<b>Key Messages and Recommendations</b>	122
7.1.	Clear, stable, and holistic policies to effectively accelerate reduction in buildings' emissions	122
7.2.	Locally-adapted design, construction and equipment: keys to new sustainable buildings	122
7.3.	Well-balanced existing retrofit solutions to significantly reduce emissions and energy use at the lowest possible cost	123
7.4.	Electrification for decarbonisation, improved integration of renewables and flexibility	123
7.5.	District heating and district cooling in selected locations: assets in abating emissions from buildings and cities	123
7.6.	Hydrogen: a limited but useful potential for buildings and cities	123
7.7.	Considering buildings as energy systems to facilitate flexibility and sustainability and enhance digitalisation	123
7.8.	Smart Cities to bring together smart buildings	124
7.9.	Renewed education and training of 'smart enterprising builders, architects and operators' and better information for the public	124
7.10.	Social measures to ensure energy transformation policies are effective	124
	<b>List of abbreviations and acronyms</b>	125

## Executive Summary

---

This chapter was developed with the cooperation of about 20 experts from all over the world, ensuring that different climate, technical and political framework conditions for the building sector were discussed.

Global buildings energy consumption amounts to about 36% of global final energy use and 37% of global carbon dioxide emissions in 2020 (iea.org), hence the importance of analysing the challenges presented by their decarbonisation.

**Section 1** presents an introduction to the topic, which summarises the main data and challenges. Decarbonisation addresses residential and non-residential buildings, including the construction and operation phase of new buildings and operation phase of existing buildings. Besides the energetic quality of the building envelope and technology, occupant behaviour has a major influence on energy consumption. Even if the energy demand per square meter has been steadily decreasing in many countries by better building standards and through refurbishment, counterbalancing phenomena, such as the so-called rebound effects, may appear.

**Section 2** is the central section and deals with the decarbonisation of buildings, both existing and new. Because of their lifespan, retrofitting existing buildings plays a major role. The energy hierarchy principle comprises the design of low-carbon low-energy buildings, the choice of low carbon materials and energy sources and applying the most efficient equipment (taking into account their affordability).

More and more buildings change from mere energy ‘consumers’ to energy ‘prosumers’ (consumers and producers) by installing photovoltaic systems or cogeneration technologies for electricity and heat. Nevertheless, generally in cities, auto-generation is either insufficient or not possible. Then electrification using electricity from the grid remains the most efficient solution to decarbonize the buildings; as the CO<sub>2</sub> content of the electricity mix is decreasing almost everywhere progressively.

Electrical space heating is one of the most promising and efficient ways where district heating systems are not available. There are many technical options for electrical heating, the most efficient one being heat pumps using ambient air, the sub-soil, groundwater, and geothermal energy, with a coefficient of performance (COP) ranging between 1.5 and 5.

More than half of the global population lives in countries where space cooling is required. Climate change is increasing the need for cooling. The major strategies for reducing energy demand for cooling are energy efficient building designs, improved energy efficiency of the cooling devices, where heat pumps play an increasing role, and low-carbon district cooling, where applicable.

The supply of hot water in buildings is another pertinent aspect. Due to low prices, photovoltaics (PV) increasingly competes with solar thermal systems, which contributes to the increasing electrification of buildings, allowing renewables to be better integrated into the system.

The next important application in buildings/homes is cooking. Today, in many emerging countries, biomass burning in inefficient and dangerous cooking stoves are still in use and need to be replaced. For the decarbonisation of cooking, electrical induction cooking has the potential to significantly bring down energy consumption and reduce greenhouse gas (GHG) emissions.

The next issue is flexibility of electrical equipment, which refers to its ability to be interruptible and adjustable, using load management systems and energy storage.

**Section 3** considers the decarbonisation of urban energy supply systems. Low-carbon district heating systems are an important option, using waste heat from power plants as well as industrial waste heat or agricultural and forestry wastes. Since the ways heat is produced will fluctuate and will not necessarily correspond with heat demand, installing seasonal heat storage would be a plus. This section addresses also heat pumps as temperature converters. They allow the bridging of temperature gaps between available heat sources and consumer needs.

This leads to a brief presentation on smart cities - principally on the energy needs of their buildings. We do not discuss other aspects of smart cities, like overall energy management, transportation, water supply, and health care.

**Section 4** deals with sustainability, public policies and regulations. A set of stable integrated policy packages is needed for the decarbonisation of the building sector, adapted to the respective climate zone. New business models can also facilitate the decarbonisation process.

**Section 5** identifies education and training as relevant aspects and preconditions for increasing the energy efficiency in the building sector. New expertise and capacity for craftsmen have to be built up, or else the refurbishment of buildings cannot increase from today's typical 1% per year rate to the 3% per year that is needed in Europe, for example, to reach the CO<sub>2</sub> reduction goals!

In **section 6** the group collected case studies: the link between regulations and building decarbonisation in some Latin American countries, the decarbonisation of a slum in Buenos Aires, and finally two case studies of district heat networks in China.

Finally, the group proposed its key messages and recommendations in section 7.

## 1. Introduction

### 1.1. Buildings' energy consumption and emissions

Building construction and operations accounted worldwide in 2020 for 35 300 TWh (127 EJ), the largest share (36%) of global final energy use of all sectors. The building sector is responsible for 37% of global carbon dioxide emissions, of which 28% is attributed to the operation of buildings and 10% to building materials and construction [<https://www.worldgbc.org/news-media/2019-global-status-report-buildings-and-construction>]<sup>1</sup>.

In many countries, the building sector is the largest consumer of energy and also the largest emitter of GHGs. This fact underlines the importance of reducing CO<sub>2</sub> emissions from this sector.

The Paris Agreement has already paved the way to engage the building sector in achieving Nationally Determined Contributions (NDCs). The sector will have to be substantially decarbonised, especially for heat consumption, which is often more challenging to decarbonise than electricity.

Though substantial work has been undertaken in many countries to develop and adopt innovative methods and technologies, in many cases it remains necessary to identify appropriate no regret strategies through systemic approaches. Such strategies must be adapted to different climatic zones, be based on benchmarks from cost-effective and climate responsive technologies in collaboration with industry and builders, and finally adopted through suitable policies and codes.

In this chapter, we try to show how to make the building a climate asset rather than a climate liability.

#### 1.1.1. Current situation: global energy demand in buildings and corresponding carbon emissions

Buildings are broadly categorised in two different sectors, residential and non-residential. The total energy consumption in buildings can be attributed to the construction and operation of these two categories of buildings. Their emissions, therefore, are of two types: embodied greenhouse gas (GHG) emissions and operational GHG emissions.

*Table 2.1.* below presents the shares of the different components of the global final energy consumption for buildings including their construction (for the year 2020) and the related carbon dioxide emissions as per GABC 2021 where data have been reported from the International Energy Association (IEA) 2021, a report *Tracking Clean Energy Progress*, which also contains many other data.

<sup>1</sup> This annual report by the Global Alliance of Buildings and Construction (Global ABC) contains many useful pieces of information and data on the sector. In the chapter, we mention these by GABC 20XX, XX for the year.

In this table, the direct emissions mentioned above are due to the direct burning of fossil fuels whereas indirect emissions are due to power generation for electricity and heat from district network. Building construction, mentioned above, includes the manufacturing of construction materials such as steel, cement and glass.

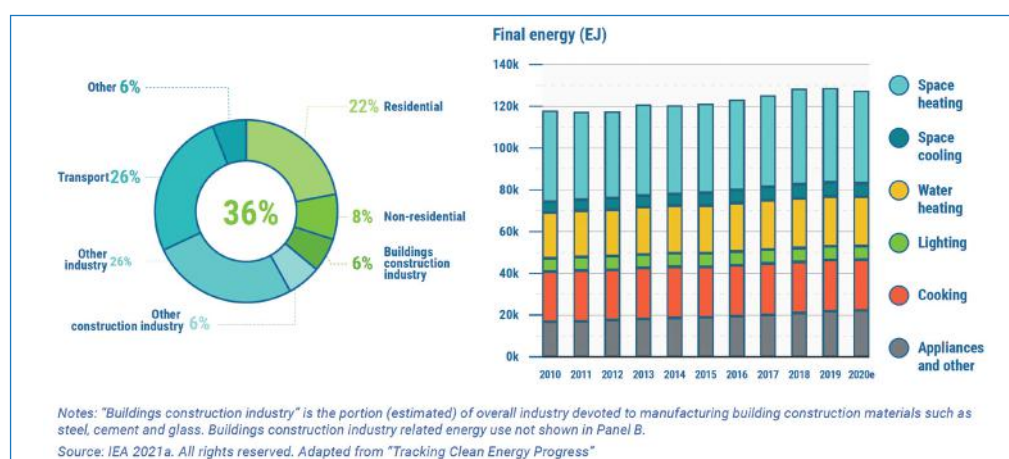
Components	Share of global final energy consumption 2020	Share of global final carbon dioxide emissions
Residential	22%	Direct: 6% - Indirect: 11%
Non-residential	8%	Direct: 3% - Indirect: 7%
Building construction	6%	10%
Total	36%	37%

**Table 2.1.** Shares of global final energy consumption and carbon dioxide emissions for buildings (year 2020)

The operation of buildings requires energy in the form of electricity and heat for cooking, refrigeration, water heating, clothes washing and drying, space heating, space cooling, lighting and for various appliances for entertainment, communication, computers and a large and growing number of electronic devices, etc.

Though space heating, lighting, water heating and cooking traditionally constituted the primary end-use energy demands in the building sector globally, in the recent past, the fastest growing end-uses have become space cooling, appliances and other plug loads (GABC 2019). *Fig. 2.1.* summarises energy consumption for the construction phase (left side) and operation/principal uses (right side) worldwide.

*Global share of buildings and construction final energy (left) and by end use (right), 2020*



**Fig. 2.1.** Final energy consumption for construction and by use

**Source:** United Nations Environment Programme (2021). "2021 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Sector", Nairobi, Page 39, Copyright © United Nations Environment Programme, 2021, [https://globalabc.org/sites/default/files/2021-10/GABC\\_Buildings-GSR-2021\\_BOOK.pdf](https://globalabc.org/sites/default/files/2021-10/GABC_Buildings-GSR-2021_BOOK.pdf)

Geographical location and climate as well as the type of the building and its characteristics affect the overall year-round energy demand of the building. The main energy applications in buildings are often for heating and cooling, depending on their location. Both depend very much on the construction and insulation standards. Existing buildings - many of them may be over 100 years old - have significantly lower standards than newer buildings: in European countries for example, the rate of new buildings is only 1% per year. Retrofitting existing buildings is thus essential for the decarbonisation of the building stock. Heating and cooling technologies play a relevant role, as the efficiency of a heat pump using ground water is many times higher than that of a 30-year-old oil boiler (many of which are still in operation). In recent well insulated buildings, the use of energy for hot water may become higher than for heating.

### 1.1.2. Adopted resolutions and challenges

To achieve the Paris Agreement goals, the United Nations Framework Convention on Climate Change (UNFCCC) Marrakech Partnership for Global Climate Action Human Settlements Pathway, co-led by Global

ABC and adopted by the #BuildingToCOP26 Coalition, set the following goal: “By 2030, the built environment should halve its emissions, whereby 100 per cent of the operation of new buildings must be net-zero carbon, with widespread energy efficiency retrofit of existing assets well underway. Embodied carbon emissions must be reduced by at least 40 per cent, with leading projects achieving at least 50 per cent reductions in embodied carbon. By 2050, at the latest, all new and existing assets must be net zero across the whole life cycle, including operational and embodied emissions.”

### *Perspectives for the Chinese and German buildings stocks*

In 2020, China announced it would achieve carbon peak by 2030 and carbon neutrality before 2060. China’s State Council released an action plan to peak carbon dioxide emissions before 2030, including for the building sector. Actions in this sector include: electrification, low-carbon heating systems in Northern China, PEDF (photovoltaic, energy storage, DC current, and flexibility) buildings, and low carbon energy systems for rural China.

In 2019, China unveiled its first-ever national Green Cooling Action Plan (GCAP). The GCAP is an integrated master plan with new energy efficiency and market penetration targets for air-conditioners and other cooling products.

In Germany, around 12.5 million residential buildings (of a total of 22 million) were built before 1977, earlier than the first German regulations on energy-saving thermal insulation in buildings. Greenhouse gas emissions from buildings were reduced from 210 million tonnes in 1990 to 118 million tonnes in 2019, thanks to energy-efficient new buildings and renovations. According to the Climate Change Act, emissions are to drop further, to just 70 million tonnes by 2030. A tax relief by 20% of the renovation costs is available for energy-efficient renovation measures such as replacing heating systems, fitting new windows, insulating roofs and external walls. Financial copensation mechanism through Federal Government programs for energy-efficient building and renovation have been increased by 10%. A maximum of EUR 120 000 in low-interest loans with a repayment grant of up to 40% for buying, renovating or building energy-efficient houses is granted. A grant of up to 45% is available to property owners who replace their old oil heating systems with more energy-efficient ones. From 2026 onwards, installations of pure oil heating systems in buildings will no longer be permitted where the adoption of a more climate-friendly heating system is possible. See <https://www.bundesregierung.de/breg-en/issues/climate-action/building-and-housing-1795860>

It may be noted that many European countries, which in the past were not requiring cooling, are now using air-conditioners because of a warmer earth. Many of these countries will have to develop regulation codes for such new applications; they may also have to retrofit the older stock of buildings.

As indicated, decarbonisation must address residential and non-residential buildings. Another distinction has to be made between existing buildings, which may be 100 years of age or older in some countries, and new buildings: for each category, adapted policies and rules are needed.

One important characteristic of the residential buildings sector is that decisions and actions for the reduction of CO<sub>2</sub> emissions involve millions of non-expert building users and owners, having furthermore often disparate and conflicting interests. Legislation should overcome several barriers: the far too time-consuming decision process carried out by the cities, conflicts of interest between building users and owners, often too long payback times for efficiency measures, and last but not least the proceedings for heritage protection.

Due to population growth, energy consumption in buildings has dramatically increased over the past decade. Moreover, longer time spent indoors, increased demand for building functions and indoor environmental quality, as well as global climate change are further reasons for increased energy consumption. The year 2020 is an exception: global energy consumption then decreased because of the economic slowdown in the pandemic period.

Significant energy savings can be achieved in buildings if the latter are properly designed, constructed and operated. Energy efficiency of buildings can provide key solutions to energy shortages, carbon emissions and the serious threats from such emissions to our living environment. Furthermore, energy efficiency has incidental

benefits, such as comfort, air quality and reducing the risk of energy poverty. Yet, attaining certain levels of energy efficiency may entail long payback periods, which may not be motivating for owners.

Abundant data and discussions on all these subjects can be found, not only in the yearly GABC report and the IEA *Tracking Clean Energy Progress* reports but also on many national and international websites, including that of the American Council for an Energy-Efficient Economy (aceee.org), the European Energy Efficiency Platform (e3p.jrc.ec.europa.eu), whose scope extends beyond the United States and Europe, and others cited later in this chapter.

## 1.2. Occupant behaviour, comfort and technical choices

We do not address here human comfort per se but occupancy and the technical choices made to obtain comfort.

A holistic approach to low-energy and low-carbon buildings implies considering the comfort desired by their users. Indeed, occupant behaviour (whether of individuals or corporations) plays a very important role in the decarbonisation of buildings. There are substantial worldwide differences in the use of energy in buildings, driven largely by behaviour and culture. Residential energy use for similar dwellings with the same occupancy and comfort levels can be improved by a factor of 3 and more and up to factor 10 in office buildings with same climate and building functions as well as with similar comfort and health levels.

Furthermore, the globalised spread of commercial air conditioning and other heating/cooling solutions induces the creation of fully-controlled indoor climates through various mechanical systems; these typically result in significantly increased energy demand.

An alternative development pathway to the ubiquitous use of fully-conditioned spaces by automatically operated mechanical systems is to integrate key elements of traditional lifestyles in buildings: the major characteristics of buildings using less energy are traditional approaches to obtain a suitable indoor climate and thermal comfort, in which windows can be opened by the building users for natural ventilation for example. Such adaptive comfort strategies take advantage of the human capacity to adapt to varying temperature conditions, at least to some extent (e.g. adapting clothing, activities etc.).

Such types of design permit ‘part-time’ and ‘part-space’ indoor climate conditioning (of temperature, humidity, and fresh air), using mechanical systems only for the remaining needs when passive approaches cannot meet comfort demands. Such pathways can reach energy use levels below 30 kWh/m<sup>2</sup>/yr as a world average, as opposed to the 30–50 kWh/m<sup>2</sup>/yr achievable through building development pathways using fully automatised maximum thermal conditioning.

Behaviours and local cultural factors can drive the basic use of energy, e.g. how people and organisations adjust their thermostats during different times of the year. During the cooling season, increasing the thermostat setting from 24 °C to 28 °C will reduce annual cooling energy use by more than a factor of three for a typical office building in Zurich, by more than a factor of two in Rome and by a factor of two to three if the thermostat setting is increased from 23 °C to 27 °C for the night-time air-conditioning of bedrooms in apartments in Hong Kong (Lin and Deng, 2004). Thermostat settings are also influenced by dress codes and cultural expectations towards attires, and thus major energy savings can be achieved through changes in attire standards, such as Japan’s ‘Cool Biz’ initiative to relax certain business dress codes and allow higher thermostat settings.

### *An example on how behaviour and lifestyle are crucial and complex drivers of energy use in buildings*

Survey results (Fig. 2.2.a.) have shown the occupancy differs in different buildings, but the total occupied time and space in residential buildings on average only accounts for 20% of full time and full space. According to the big data analysis based on China’s VRF (Variable Refrigerant Flow) operation, the operation behaviour is “part time and part space” instead of “full time and full space”. Fig. 2.2.b. indicates that, during the whole operation period of VRF’s outdoor unit, more than half of the time only 1 indoor unit is operating, and more than 80% of the time there are only 2 indoor units operating. Most of the monitored families with VRF systems are high-income families, therefore, these data revealed the “part time and part space” demand is the real demand, instead of that limited by economic and cost reasons. However, towards the “part time and part space” demand, different systems would lead to significant energy intensity differences. With “full time and full space” systems like centralised HVAC (heating, ventilation and air-conditioning) system in residential buildings, the cooling energy intensity is more than five times higher than decentralised VRF systems with

“part time and part space” service. On-site measurement of more than 600 apartments in five similar residential buildings in Beijing in 2006 found that households using mini-split ACs used less energy per m<sup>2</sup> for cooling than those neighbours using multi-split units, shown in Fig. 2.2.c.. The average cooling electricity intensity of apartments in a building with a central HVAC system was more than four times greater, reaching nearly 20 kWh/m<sup>2</sup>. In summary, investigation of real occupant behaviour and proper system type choice are key issues to achieve suitable building indoor service and low-energy consumption.

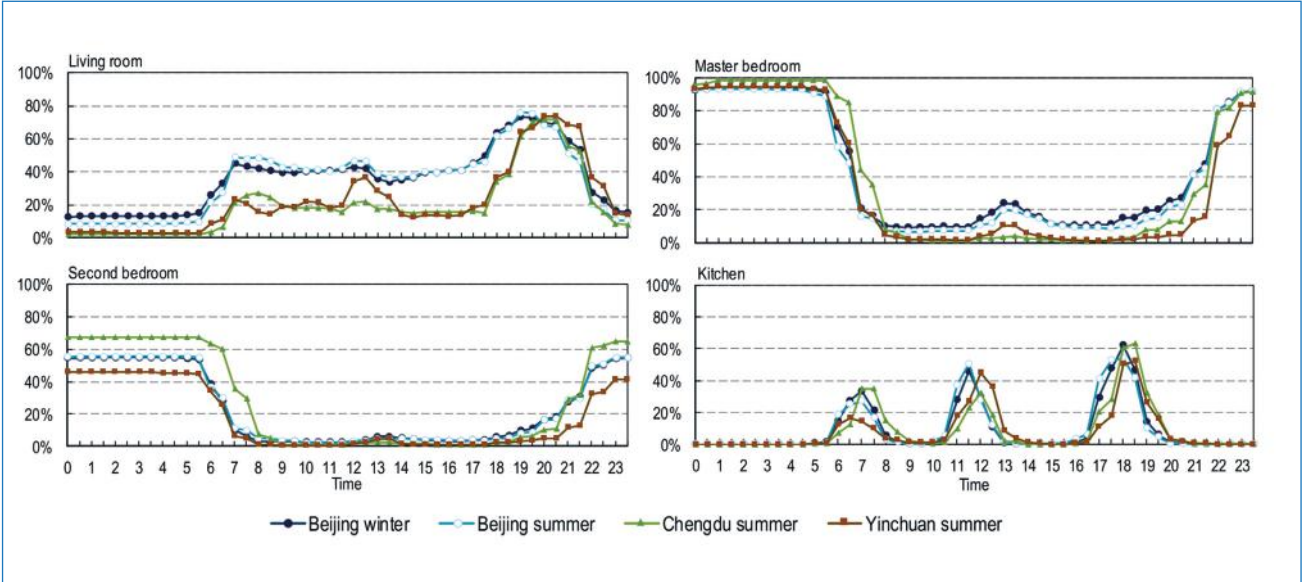


Fig. 2.2.a. Occupancy rate of urban households in China (data source: questionnaire survey on 3 400 households in 4 Chinese cities) (Hu et al. 2019)

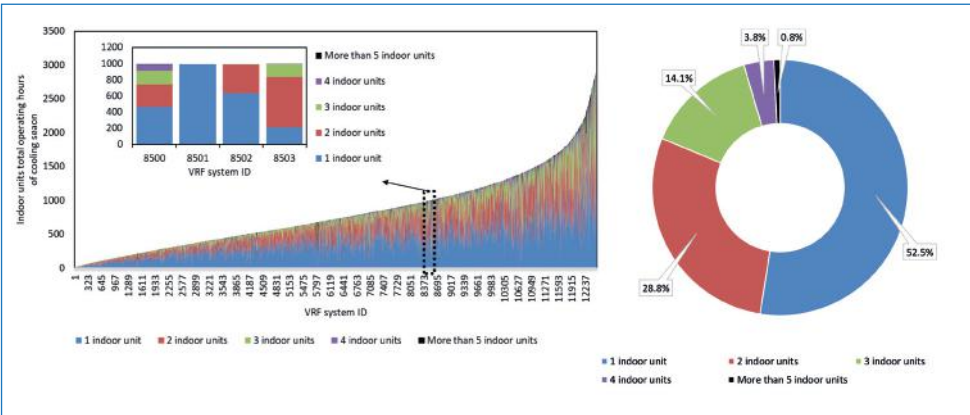


Fig. 2.2.b. VRF operation patterns of urban households in China (data source: 12 527 VRF systems operation monitoring data in residential buildings in

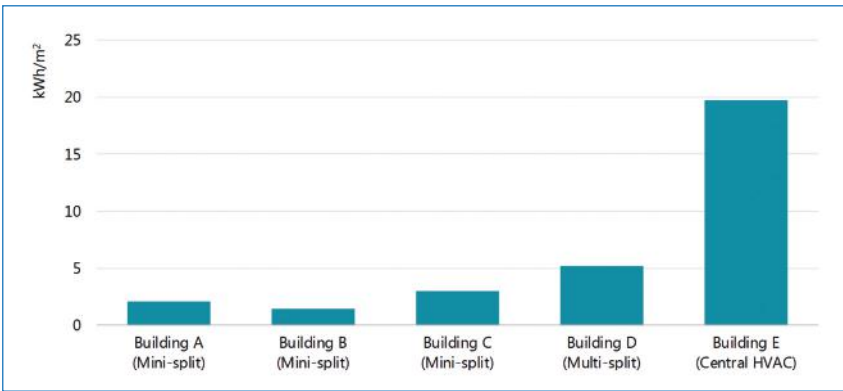


Fig. 2.2.c. Average cooling energy intensities by different system in urban residential building (data source: monitoring of 5 buildings in Beijing in 2006)(IEA, 2019)

Three other dimensions have to be mentioned:

- The introduction of automations, at the same time, reduces the use of equipment (heating, cooling, lighting, etc.), the energy bill, and the emissions. It is usually welcomed by the users if they can regain control when they want or need.
- Numerous experiences have been made to inform in real time the user/customer on their mobile phone or on a screen in the kitchen for example about their consumption: cost savings are usually low, and do not motivate users. Nevertheless, individual meters measuring energy consumption and indicating the level of the future bill may have an impact on consumption.
- The standardisation and simplicity of the equipment's interface with the users are key for their effective use, even more so for people with impaired reading abilities, but also to make it easier for new residents, who will not have to get used to different equipment when changing their apartment or home.

While in many countries the construction of new homes and the refurbishing of older ones has entailed decreasing energy demand and GHG emissions per m<sup>2</sup>, some counterbalancing effects may appear. They are described below:

1. The rebound effect, when, for example, better insulation allows occupants to opt for higher temperatures at the same cost. In such cases, energy consumption and emissions are not necessarily decreasing as foreseen.
2. Higher living standards may allow the acquisition or renting of larger homes or apartments, such as for example in Germany, where the average room space did more than double in the last 50 years.
3. For the same rent/price, citizens may have the choice, e.g., between modern flats in the city near their working places or a larger, older family house outside the city. The difference for the latter choice at the level of energy consumption and emissions (heating/cooling, driving) easily amounts to a factor 4.

## 2. Decarbonisation of buildings' energy consumption

Assuming that the development in additional cooling applications in buildings will be very dynamic in most countries, leading to better living conditions in hot emerging countries and also under the conditions of climate change. This section focuses on the situation in developing countries and does therefore not report into much detail on heating technologies. Instead, it focuses on cooling and cooking applications as well, as on the situation of millions of families, which is still not satisfying in view of health, safety, comfort and CO<sub>2</sub> emissions.

### 2.1. Buildings' efficiency: existing and new buildings, architectural design and construction

#### 2.1.1. Retrofitting of existing buildings

In most countries, the existing buildings stock is a major energy consuming factor. The characteristics of these buildings (walls, windows, roofs, insulation, ventilation, etc.) have often extensive scope for improvements in energy efficiency through retrofitting. Yet, while technically feasible, the owners of such buildings have reservations about investing in such enhancements as the payback period may be too long for them to consider the investment to be reasonable. Furthermore, regardless of the benefits in terms of comfort (e.g. acoustics) the payback period is not clearly predictable, as it depends on the retrofitting quality and possible rebound effects.

A number of countries have already introduced several measures through a variety of policy interventions, though often in a less rigorous manner than for the requirements that apply to new buildings, such as support or requirements for individual measures (e.g. insulation, new windows, heaters with performance labels) rather than approaches for whole buildings, despite the fact that the latter can deliver the best cost-effective results.

The aspects mentioned in the last two paragraphs demonstrate the importance and difficulty of defining a 'low-regret strategy' and to apply it in the field. For more elements on 'low-regret strategy', the reader may refer for example to the 2021 report *Rapid 'low-regrets' decision making for net zero policy* from the UK's Royal Academy of Engineering (RAEng).

Equipment for different needs (heating and cooling, lighting, cooking, water heating, refrigerators, air-conditioners and other building-related appliances) has seen remarkable efficiency improvements in the last twenty years. These improvements should be applied as much as possible to existing buildings. While some equip-

ment is directly using the sun (e.g. for water heating), most equipment is electric, which mean it is 'low-carbon' as soon as the electricity is low-carbon.

One should also identify the low-hanging fruit for emission reduction in the building stock of the country, region or city under consideration (such as commercial and institutional buildings). Some of the business models to achieve the mentioned goals that are successfully being adopted in some countries are described below:

#### *The Energy Service Companies (ESCO) as business models for retrofitting*

ESCO is a company that offers energy services, such as design, retrofitting and the implementation of energy efficiency projects after identifying energy saving opportunities through the energy audit of existing facilities. It also includes energy infrastructure outsourcing, power generation and energy supply, financing or assisting Facility's Owners in arranging finances for energy efficiency projects. ESCOs operate by providing a savings guarantee, risk management in the implementation of energy efficiency projects. Moreover, they also perform measurement & verification (M&V) activities to quantify actual energy savings after the implementation of energy efficiency projects, etc. The ESCO business model allows companies to carry out energy services without the clients having to invest their own capital into the projects.

The ESCO concept started in Europe more than a century ago and spread to North America. In the last few decades, because of increased interest in the provision of energy services, the ESCO movement has widely spread all over the world.

#### *Example from India*

In India, significant energy efficiency potential is left untapped. The Bureau of Energy Efficiency (BEE) of the Ministry of Power of the Government of India encourages ESCOs by offering training and capacity building and therefore qualify ESCOs for taking up related projects. ESCOs are considered to be the main vehicles to harness this untapped energy efficiency potential of the country. The BEE, through various programmes, brings together end-users, ESCOs, technology providers, financial institutions, distribution companies (DISCOMs), Government agencies, etc. on a single platform to accelerate the uptake of energy efficiency projects through the ESCO route.

#### *Example from South Africa*

The South African National Energy Development Institute (SANEDI), in collaboration with the Department of Mineral Resources and Energy (DMRE) and the *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ), established a national register for Energy Service Companies (ESCO register). The ESCO register is used by both the public and private sector organisations to identify, plan, develop, finance or implement energy efficiency projects, including energy efficiency demand side management and small-scale embedded renewable energy generation.

More recently, the World Bank partnered with SANEDI and the DMRE to drive opportunities in the large-scale demand-side energy efficiency market in South Africa. This is being done through a request for consultants' expressions of interest (EoI) to assist with ESCO market development and technical assistance, which was launched by the World Bank in June 2021. SANEDI notes, "The appointed consultant will build on international best practices to identify feasible paths for transformative development of the ESCO industry in South Africa that could effectively contribute to untapping the large-scale demand-side energy efficiency market"

Creamer Media Engineering News, 16 July 2021, by TASNEEM BULBULIA

### 2.1.2. New buildings

According to Future of Construction, a forecast report produced by Oxford Economics and Marsh McLennan subsidiaries Marsh and Guy Carpenter, construction will be a vehicle for global economic growth in the decade to 2030 with output expected to be 35% higher than in the ten years to 2020. Further, it has been projected by many other reports that this spur in building construction activities will continue until 2050, especially so in the countries with growing economies. Because of increasing population, economic growth, the rising aspirations for improved lifestyles and rapid pace of urbanisation, these countries, many of which are in tropical and warm climatic region, will experience a dramatic increase in the demand for energy for building construction and operation. As a result, global building energy consumption and related GHG emissions will continue to rise at a very high rate unless drastic action is taken to decouple growth and emissions.

Extensive work has been accomplished in many countries for the design, construction and operation of new buildings in a climate-friendly manner, bringing down energy use and emissions both for construction and operation of these buildings. It is important to note that the lifetime of buildings is typically at least 50 years, and therefore the specific GHG emission levels will be locked-in for decades based on the ways buildings are constructed.

It is thus desirable, for the purpose of decarbonisation, to exchange guidelines on how to possibly design, construct and operate buildings in a “greener” way based on the work carried out by many countries for different climatic conditions.

The ‘energy hierarchy’ principle proposed in this report involves:

1. Passive design: as the first step in creating energy-efficient buildings to reduce energy demand, it implies that the best possible and affordable design in the local context will bring down the annual cost of operation of the building throughout its lifetime.
2. Choosing the right available low-carbon materials and energy sources/vectors: direct solar use (for water heating for example), geothermal heating or cooling, low-carbon heat from district network, low-carbon electricity from local PV or from the network.
3. Choosing the most efficient equipment using the chosen sources/vectors, taking in to account their affordability.

Concerning the design:

- The orientation of buildings and their walls and windows as well as the colouring of their roofs is a crucial factor in maintaining comfortable temperatures inside.
- Passive design strategies are by nature easier to integrate into buildings during their construction phase, and even more so when larger developments are concerned, where designs can take advantage of opportunities at the wider scale in terms of buildings and street layout, prevailing winds, developing neighbouring green areas or bodies of water, etc.

Architectures should prioritise passive measures. Then active optimised measures should be considered when all passive options are fully adopted. The objective of passive design architecture is to produce a suitable indoor environment quality by taking advantage of the natural surrounding environment and resources, including natural lighting, natural ventilation, free heating and cooling, etc. The optimisation of building design can substantially reduce the buildings’ demand for energy. This can be particularly effective in the case of natural ventilation and shading devices when the outdoor temperature is suitable. Standards and guidelines in this respect have been developed in many countries:

- volume factor, window-to-wall ratio, transparent envelope ratio;
- building layout, including the positioning of uses according to orientation; favouring dual-aspect dwellings and buildings to encourage cross-ventilation and provide users with a choice of openings on different facades depending on the sun, light, noise levels, etc.;
- heat transfer, heat storage and the light transmission properties of walls, roofs and windows;
- the radiation characteristics of the external surface material of buildings;
- improved airtightness, enhanced natural ventilation, adjustability;
- natural lighting and glare avoidance;

- humidity regulating and moisture storage material on the inner surface of the wall so as to maintain indoor humidity.

To summarise, inbuilt energy efficiency due to passive design, will always bring down the annual cost of operation of the building throughout its lifetime.

Concerning the construction materials, it is worth mentioning that the design of the structure and choice of the materials are linked. In order to reduce especially the need for heating and cooling, low-carbon materials, if possible local ones, should be used as much as possible.

A growing number of materials able to contribute to decarbonisation of buildings are already available or at an industrial demonstration phase. A few examples:

- ‘green’ cements, to replace Portland cement, engineered woods such as glue-laminated beams and cross-laminated timber composed of multiple layers of smaller board;
- adaptive insulation materials shielding from cold and taking advantage of solar gains; phase-change materials to store energy, reduce consumption and enhance comfort; active and selective insulating glazing, produces energy via photovoltaic cells, and filters sunlight to avoid glare;
- prefabricated elements (prebuilt on an industrial scale), manufactured small homes and on-site 3D-printed homes, ensuring ease and quality of installation;
- wood-framed buildings, which require less energy and induce less GHG emissions than concrete-framed buildings.

To improve the quality of buildings, which has positive consequences on energy consumption and emissions, far more digitalisation would be useful: the use of Building Information Modelling (BIM) allows information to be managed during the entire lifetime of the building from design to construction, operation and maintenance.

### 2.1.3. Buildings with PV external surfaces as energy ‘prosumers’

Space has become a valuable resource for renewable energy development. With the dramatic decrease of PV system costs, distributed PV systems are more and more used in rural and urban areas. Suitable policies (incentives, special types of tariffs for the electricity generated) may facilitate PV integration in buildings. Building distributed PV can be carried out simultaneously with building design and construction (or installed on existing building roofs when possible) which avoids using land areas as centralised photovoltaic power plants do.

In the future energy system, the role of buildings will switch from consumer-only to prosumers, e.g. mainly with in-house electricity generation by PV. Solar PV should be adopted taking full advantage of building rooftop and façade space. Building Integrated PV (BIPV) and Building Attached PV (BAPV) would become future trends of architecture design optimisation and space utilisation, through:

- BIPV/BAPV technologies after evaluating the space resources of building surface
- Indoor environment control with BIPV/BAPV measures: considering the indoor thermal environment and the real time power generation.

Rooftop Solar PV (RTS) has been expanding very fast in many countries. Apart from greening the building, the other major benefits for installing these systems are that the user can get the RTS system installed on the vacant space of the roof of the building (with a variety of configurations that may allow utilising the space under the PV panels) and the electricity produced is utilised at the point of generation without any transmission and distribution loss. Many countries have made appropriate modifications of their electricity regulations that allow RTS or BIPV or BAPV systems to be connected to the grid with adapted metering and billing. Thus, the building can use the solar electricity it generates during daytime whenever required, can export it to the grid when it is not used or in excess, and can seamlessly receive electricity from the grid during night or whenever the solar electricity produced is not sufficient. A number of business models are now also in place that allow the user to either make their own investment for installing and operating the system (capital expenditure (CAPEX) model) or make arrangements with a developer to make the investment for installing the solar system on the roof of the building and operate it. The electricity will then be purchased by the user for a certain number of years (RESCO model). As the cost of PV has been drastically decreasing, many users find business sense in opting for such solar systems.

## 2.2. Electrification

Electrification with low-carbon electricity is certainly the major avenue for decarbonisation. Keeping in view the recent progress of global electrification, the increasing ubiquity of use of appliances and equipment in buildings, and the SDG targets, we can consider electricity as the basic infrastructure for the building sector, its speed of implementation depending on the country or region.

With more and more low-carbon electricity, electrical solutions are becoming the least emitting and more energy-efficient solutions in comparison with using fossil fuels (coal, gas, petrol). Yet, while producing incidental benefits such as flexibility and the avoidance of local pollution, depending on the local relative price of electricity and fossil energy, the cost related to the electric solutions may be higher than that for using fossil fuels.

### 2.2.1. Heating

The space heating of buildings should be adapted to climate conditions and local resources.

In regions with district heating systems, such as China, Russia, Germany and other Nordic countries, district networks are a good resource to collect various low-temperature heat sources. Achieving low-carbon emission heating by low-carbon heating sources (waste heat from industrial process, biomass fuel thermal plants, exhaust heat from data centres, and so on) is the principal issue.

In regions with no waste heat and district networks, electrical heating should be promoted. Electrical heating has many technical options: direct heating systems via air or via radiation, standalone systems including night storage heaters or heaters integrated in the floor or the walls. It is obvious that a heat pump operated with low-carbon electricity, in particular solar and wind electricity, using ground heat and supplying a new house at low flow temperature is a more sustainable solution than electricity from coal or heat from a gas fired district heating system.

Electrical heat-pumps are regarded as a key technology to increase energy efficiency, in combination with ongoing increases in low-carbon electricity. Electric heat pumps may be optimised for new low-energy buildings but also as a substitute in existing buildings with boilers and radiators. Heat pumps may have a COP between 1.5 to 5, depending on the flow temperature and the temperature spread between the source and the room (Carnot's law).

A possible heat source is ambient air but, when possible, using ground, ground water, shallow geothermal energy (from 3 meters to 100-200 meters deep), district heat or waste heat from grey water or sewage, is more effective since, at least in winter, these sources reach higher temperature than air and they have smaller temperature variations (See *Section 3.*). The flow temperature needed is about 30 °C in new buildings with floor heaters and up to 60 °C for older buildings and for drinking warm water.

Air source heat pumps can be used in regions where outdoor temperature during winter is above – 10 °C and the COP may be more than 2.5. The key technical barriers of air source have been resolved by new compressor technology, variable frequency technology and new system forms, and the applicability of low temperature air source heat pump heaters has been extended to regions with – 30 °C outdoor temperature. Nevertheless, large outdoor temperature variation leads to lower energy efficiency across the heating season, lower operational reliability issues at high compression ratios, and insufficient heat supply at ultra-low outdoor temperature. Increasing enthalpy by double-stage compression technology and other technologies can overcome such shortcomings and achieve high-energy efficiency at low ambient temperatures, so that the use of heat pumps extends to a wider span. The air source heat pump, based on double-stage inverter compressor and air replenishment enthalpy increasing technology, can effectively solve the problem of heat decay in low outdoor temperature. The energy efficiency could reach 3.1, which is 10%~15% higher than normal air source heat pump. Frost is another important working issue under high humidity environment. Reverse cycle defrosting, hot gas bypass defrosting, thermal storage defrosting and ultrasonic defrosting could effectively solve the frost problem. The optimisation of indoor airflow organisation by distributed air supply terminals could furthermore improve the level of indoor comfort.

## 2.2.2. Cooling

### *Energy demand for space cooling*

More than half of the global population live in countries that require space cooling. Cooling degree days (CDD) are projected to continue increasing during the next decades, with biggest increases occurring in already hot places where income and population are rising fastest. Access to space cooling is a critical development need to improve the quality of life, health, education and also productivity (IEA 2018a). Furthermore, with global warming, there will be increasing demand for cooling, including in the countries which traditionally have arrangements for space heating only. As a result, global building energy consumption and related GHG emissions will continue to rise at a high rate (see IEA2018a). If immediate appropriate measures are not taken, the state of technologies and a part of the GHG emissions will be locked in for decades.

GSR 2021 reports that according to the IEA, energy use for space cooling doubled since 2000 – from 1 000 TWh to 1 945 TWh – due to hotter weather conditions, rapid urbanisation, the diffusion of air conditioner ownership and use of inefficient air conditioners (Cooling Post 2018). The projected growth in residential and commercial space cooling capacity from 11 670 GW in 2016 to over 36 500 GW in 2050 (See *Cooling Emissions and Policy Synthesis Report*, published in 2020) could leave substantial cooling needs unmet.

Air conditioning may contribute to 50-80% of peak demand in hot climates (Khalfallah et al. 2016). Peak power is usually the most carbon intensive, polluting and costly electricity, straining electricity grids. Consequently, space cooling is an increasingly major carbon contributor among building end uses, emitting around 1 gigatonne of carbon dioxide annually (GSR 2021).

### *Strategies of decarbonisation for cooling*

The following strategies for decarbonisation may be put forward, keeping in mind that the principal energy source for cooling is electricity.

#### **1. Take advantage of the climatic zones of the world.**

This is one of the major strategies to meeting cooling demand with minimum electricity consumption and carbon and other GHG emissions. It provides the appropriate background to define the national codes for energy-efficient and climate-friendly air-conditioner systems for different categories of buildings in a particular region.

The world could be divided into three principal kinds of climate regions, as shown in *Fig. 2.3.*:

- a. Dry regions, as shown in blue, include most countries in Europe, parts of countries in Asia (including the northwest side of China, Mongolia, Saudi Arabia, Kazakhstan, the middle of India and so on), Northern Africa, most parts of Australia, the west side of the United States and southwest areas of Canada, where Indirect or Direct Evaporation Cooling (IEC or DEC) technologies could be used for air conditioning, instead of mechanical refrigeration systems.
- b. Cool and humid regions, including parts of countries in Europe, especially around the Mediterranean Sea, parts of regions in the United States and Canada, parts of regions in Asia, such as the northeast side of China and so on.
- c. Hot and humid regions, including parts of regions in Asia, such as the southeast side of China, parts of India, parts of regions in the United States and also parts of Central and South America.

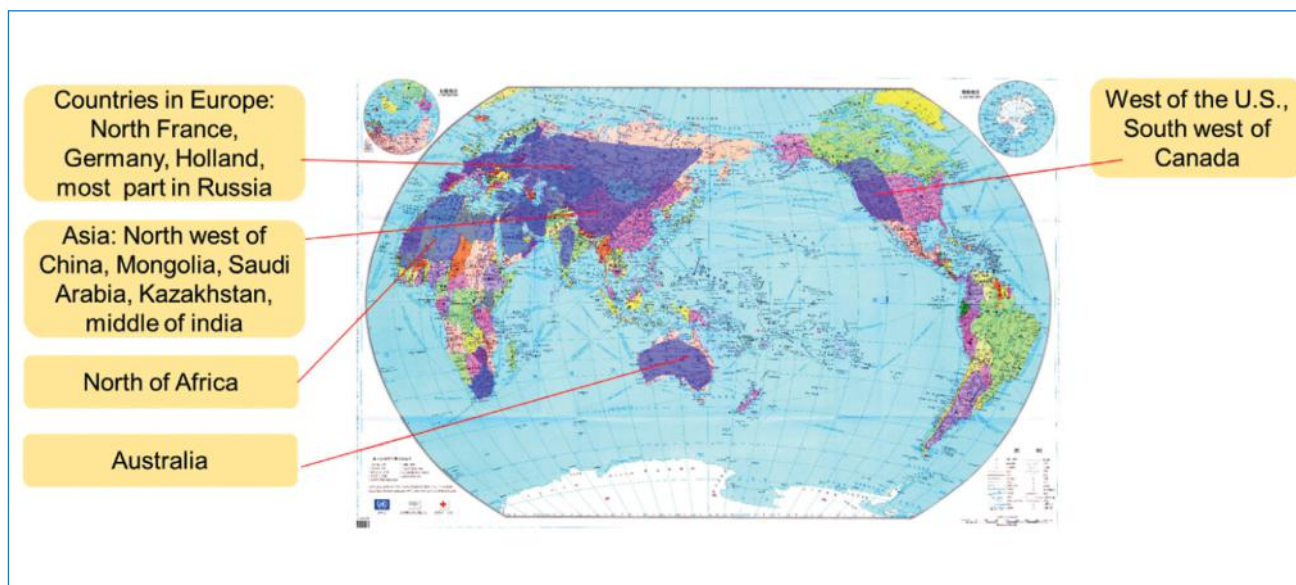


Fig. 2.3. Regions of the world where IEC or DEC technologies may be suitable

Suitable cooling technologies could be developed/optimised according to the different climates in the world.

**2. Design energy-efficient new buildings or retrofitting strategies for existing buildings, thus also reducing cooling as well as heating needs.**

- A number of solar passive features have now found appropriate place in the energy-efficient building design guidelines published in different parts of the world.
- Existing buildings can be suitably modified by incorporating appropriate insulation technology, energy efficient windows, judicious choice of ventilation, energy management systems etc.

Furthermore, plants grown for shade in summer and letting light enter in winter are useful.

**3. Increase the energy efficiency of cooling devices** (air-conditioners, fans etc.) to reduce electricity consumption and, therefore, carbon emissions. Many old air-conditioning systems which are still used are inefficient and not well installed. High-efficiency air-conditioners with appropriate refrigerants that have much lower global warming potential are now available. Appropriate guidelines for installing new air-conditioning systems need to be developed and their implementation should be promoted.

**4. Use direct electrification of cooling demand with local renewables**, as much as possible.

Buildings with mostly day-time cooling requirements (educational institutes, office buildings, a few industries etc.) can have their own decentralised green energy generating systems. Examples include rooftop solar PV, small wind turbines in windy areas, electricity generating systems, etc. However, there must not only be suitable electricity regulations that permit such local use but also integration of these electricity generating systems with the grid and appropriate metering systems.

**5. Define and mandate cooling standards** (cooling temperature set point).

More than 80 countries already have minimum energy performance standards (MEPS) for air conditioners, with additional standards currently under development in over 20 countries. These standards vary considerably from one country to another (IEA Nov 2021) and considerable improvements can be made in many countries. It has also been observed that MEPS are generally weaker or absent in hot and humid regions where rapidly increasing AC demand is expected.

Standards and guidelines for cooling systems require periodic review in order to tailor the adoption of new developments to the climatic zone under consideration. Guidelines are also required to be issued by the governments for major commercial and institutional establishments with the objective of conserving energy through optimum temperature settings of air-conditioners within the comfort zone/chart. As noticed in *Section 3.2.* of this chapter, setting the temperature from a presumably conventional 20-21 °C to 28 °C for example can result in substantial energy savings and concomitant carbon emissions.

#### *Chinese and Indian cases*

For energy conservation purposes, the **Chinese State Council** and MOHURD (Ministry of Housing and Urban-Rural Development) require indoor air conditioning temperatures to be controlled and no less than 26 °C in public buildings, through a decision document.

Source: [http://www.gov.cn/govweb/fwxx/sh/2006-09/01/content\\_375201.htm](http://www.gov.cn/govweb/fwxx/sh/2006-09/01/content_375201.htm)

The **India cooling action plan** (ICAP) was launched in March 2019. The plan seeks to reduce cooling demand, refrigerant demand and cooling energy requirement. This plan also mentions research and development, and training and certification in cooperation with Skill India Mission.

## 6. Alternative cooling systems.

- Evaporative coolers (that extract energy from the air to evaporate water) in appropriate shapes and sizes, with energy efficient fans and pumps, as well as with suitable solar power systems, must be considered. These are very effective for residential and office use in areas and in seasons with low humidity. The necessary supply of water they require may, however, create problems in many areas.
- Cooling systems (absorption or adsorption) based on solar thermal heat (or waste heat) for institution buildings which need cooling mainly during daytime, must also be considered.

*Status of Cooling initiatives* (as reported at COP 26 by Clean Cooling Collaborative - a philanthropic initiative working to create a future with efficient, climate-friendly cooling for all)

A number of other cooling commitments were made in the run-up to COP26, setting the stage nicely for others to take similar steps. Highlights include bringing super-efficient air conditioners to the market, developing national cooling action plans, mapping pathways to sustainable cooling, and devoting sizable amounts of funding to the support of clean cooling globally. The Cool Coalition's Cooling Commitments Compass (see below) gives an overview of recent announcements and updates from around the world of cooling.

### 2.2.3. Domestic Hot Water

The most suitable options will be context-specific, taking account of such factors as:

- the use profile, how well this matches the generation profile, and the ability to incorporate storage to maximise the use of renewable generation in the case of PV systems and/or make use of grid electricity at times of low demand;
- climatic conditions, and whether they are better suited to solar thermal or PV generation;
- market prices and product availability;
- energy prices, and whether top-up is needed to complement on-site renewable generation (for example, in some countries, electricity is expensive and using it to top-up electrical hot water heating could be detrimental to users).

According to the domestic hot water survey, different vectors of energy are used to heat water, especially electricity, gas and solar energy.

The solar domestic hot water (SDHW) system has been developed rapidly in the past decade to reduce fossil energy use. As other renewable energy technologies, the solar domestic hot water system is characterised by higher upfront investment costs and lower operation and maintenance (O&M) costs than conventional technologies. Investment costs for solar water heating depend on the topology of the system, market conditions of different countries and labour costs. As initial investment in SDHW systems has decreased, they have become affordable for more and more people in many countries.

With the rapid development of the solar photovoltaic (SPV) technology, prices have decreased by more than 85% in the past 10 years. The current initial investment for the SPV system is about USD 0.6 per Watt-peak in 2021. Compared with the solar thermal system, the O&M cost of the SPV system is ever lower. As a consequence, the SPV system has more and more advantages over the solar thermal system in terms of system cost, efficiency, and O&M. Solar PV should be promoted as the main source of domestic hot water, and, in turn, domestic hot water provides flexible load to compensate for unstable solar energy, which can benefit the promotion of solar PV.



Fig. 2.4. Comparison of solar domestic hot water system and photovoltaic system

The heat pump water heater with CO<sub>2</sub> as a refrigerant is also a good technology for domestic hot water production, and it has been widely promoted in Japan by electrical utilities. The associated water heater manufacturers even nicknamed 'Eco Cute' the heat pump water heaters that use natural refrigerant CO<sub>2</sub>. Rotary, swing and scroll are the three main types of compressors applicable to the current CO<sub>2</sub> water heat pump. To reduce the high throttling loss resulting from the high-pressure difference of CO<sub>2</sub>, two-stage compressor and expander technologies have proved to be quite effective solutions.

### Hot water heating in South Africa

The South African National Building Regulations (NBRs) Part XA Environmental Sustainability, Energy Usage in Buildings, lawfully requires that at least 50% (volume fraction) of the annual average hot water heating requirement shall be provided by means other than electrical resistance heating, including but not limited to solar heating, heat pumps, heat recovery from other systems or processes and renewable combustible fuel.

#### 2.2.4. Cooking

Cooking is a universal and substantial energy requirement in buildings. Various methods and a variety of fuels are used for cooking. A large portion of the world population still use cook stoves and fuels that are inefficient, polluting and responsible for carbon emissions and may create stress to local natural resources.

##### *Introduction*

Since time immemorial, humans have been using various forms of biomass as fuel to cook their food. The efficiency of these cook stoves with a variety of biomass fuels were never very high. This might be because in ancient days biomass was not at short supply, and also because people around the world developed different kinds of cooking habits that did not require efficient stoves. Even after the arrival of coal as a convenient fuel, the situation did not change as far as the efficiency of stoves was considered.

As a consequence of incomplete combustion, kitchens have always been filled with smoke and black tar. Cleaner fuels, such as coal gas, natural gas, liquefied petroleum gas (LPG), biogas, but also electricity, entered the scene only since the late nineteenth century. Still, depending on the geography, traditional fuels (coal, wood, charcoal, dung or other kinds of solid fuels and kerosene) are still predominantly used in many countries. Even after half a century of programmes on providing access to clean cooking, the world falls short on its progress towards the Sustainable Development Goal (SDG) 7, achieving universal access to affordable, reliable, and modern energy services (The World Bank Briefs, November 2020). These programmes mainly targeted the improvement of cookstove efficiency to ameliorate solid fuel combustion and reduce the emission of smoke and carbon shoots as well as the use of the above-mentioned fuels.

Efforts, however, are now being made to revisit these programmes on cooking, not only to provide clean cooking at the point-of-use but also to decarbonise cooking.

##### *The current situation for cooking*

In many countries of the developing world, a large percentage of households still follow traditional cooking methods using the above-mentioned fuels to cook on stoves made of mud, bricks or stones, which are extremely inefficient in fuel utilisation. According to the 2020 edition of Tracking SDG 7, The Energy Progress Report, 2.8 billion people in the world still do not have access to clean cooking fuels and technologies.

Reasons attributed for practising traditional cooking methodologies include the poor economic conditions of many households, absence of alternative cooking fuels even if a small percentage of households can afford it, and absence of concrete planning and appropriate actions by the governments.

##### *Challenges for cooking*

Particulates (e.g., small particles resulting from the combustion of hydrocarbons), contain a large number of health-damaging air pollutants. Traditional cookstoves emit particulates. It is nearly impossible to go beneath some level of emission, particularly if utilising a solid or liquid fuel. In many cases, the poorly ventilated kitchens with such cook stoves get filled with concentrated emissions negatively affecting the users. Mothers, pregnant women, and young children are disproportionately affected, as they are typically responsible for household cooking and firewood collection (The World Bank Briefs, November 2020). Household air pollution, mostly from cooking smoke, is linked to about 2.5 million premature deaths annually. (Access to clean cooking – SDG7: Data and Projections – Analysis, IEA, October 2020. Retrieved 2021-03-31)

Clean cooking is thus an urgent global development issue since more than 2.5 billion people in the world have no access to clean cooking fuels and technologies. To decarbonise the cooking sector, each country should assess all available modern cooking fuels and technologies to identify what is right for the country, taking into account local cooking practices in their complexity.

##### *Existing, forthcoming and possible breakthrough solutions for cooking*

The efficiency of rudimentary cookstoves relatively to heat utilisation is very poor, and may even drop to a level lower than 10%.

A number of improved cookstoves for burning solid fuels have been developed and implemented. Many of these more efficient cookstoves reduce fuel use by 30-60% and ensure more complete combustion. Recent evidence also demonstrates that advanced (efficient and low emission) cookstoves and fuels can reduce black carbon emissions by 50-90% (Clean and Efficient Cooking Technologies and Fuels, USAID & Winrock International, September 2017).

Continuous developments of the design of the cook stoves based on modern gaseous and liquid fuels (such as coal gas, natural gas, liquefied petroleum gas (LPG), biogas, kerosene, ethanol, etc.), as well as electricity, have resulted in standardised designs with higher fuel use efficiency and lower emissions. These standardised new cook stoves are now used by around two third of the global population. In many countries, national guidelines discourage the household use of kerosene and unprocessed coal.

Gas stoves are widely used globally because they offer instant heat and provide easier temperature control. All varieties of cooking can be undertaken with these stoves. These stoves, however, compromise indoor air quality, especially if not fitted with an exhaust hood. Gas stoves emit nitrous oxides (NO<sub>x</sub>), carbon monoxide (CO), and formaldehyde (HCHO). However, as noted earlier, emission reductions are much simpler and easier to obtain with gaseous fuels than with solid fuels. On natural gas cooking, it has been reported that natural gas stoves also emit 0.8–1.3% of the gas they use as unburned methane<sup>2</sup>.

Electric coil stovetops are convenient to use. However, these stoves have thermal inertia, which results in waste heat, and remain hot after cooking, which is dangerous. But these stoves do not emit any indoor air pollutant.

Induction cooking works with far less electricity and is very flexible. Considered as one of the most efficient cooking technologies, it works only with cookware containing ferrous metal. In induction technology, the flow of an alternating current (AC) through the 'element' creates an electromagnetic field that excites the molecules in ferromagnetic pots and pans placed on top of the glass stovetop. As a result, up to 90% of the energy consumed is transferred to the food, compared to about 60% to 70% for traditional electric systems and around 40% to 50% for gas. These stoves neither emit much heat outside, nor any indoor air pollutant<sup>3</sup>.

Concerning CO<sub>2</sub> emissions, considering that, to obtain 1 kWh by gas combustion, about 200 g of CO<sub>2</sub> are emitted, and considering that the efficiency is double with an induction stove compared to a gas stove, induction stove emissions are thus less than gas stoves as soon as the electricity mix contains less than 400 g of CO<sub>2</sub> which is the case in more and more areas.

### *Conclusion and recommendations for cooking*

The trend of electricity mix in many countries towards low-carbon electricity strongly supports induction cooking as the desired equipment to decarbonise the cooking sector in the near future. Based on sound technical reasoning, it can be projected that the cooking sector of the industrially developed countries can move towards induction cooking from gas cooking or traditional electrical cooking because of its reliable electricity infrastructure, which is becoming greener over time, a strong industrial base with testing and standardisation facility, widespread network of sales and servicing, and the capacity of the population in general to purchase induction cookers.

Nevertheless, the efforts of introducing efficient cookstoves in place of traditional inefficient ones must continue on a war footing to provide clean cooking at the point of utilisation for a vast part of the developing world. It may be noted that biomass cooking, if implemented with the best possible efficiency, has also its inherent contribution towards the decarbonisation of the cooking sector.

In parallel, in many emerging economies and especially in Africa, governments are developing policies for solar -based cooking in areas lacking electric networks: a PV panel, a battery for storage and an adapted well- insulated chamber is then able to replace inefficient cookstoves<sup>4</sup>.

<sup>2</sup> Methane and NO<sub>x</sub> Emissions from Natural Gas Stoves, Cooktops, and Ovens in Residential Homes: Eric D. Lebel, Colin J. Finnegan, Zutao Ouyang, and Robert B. Jackson, *Environ. Sci. Technol.* 2022, 56, 2529–2539).

<sup>3</sup> See for example: The Electrification of Cooking Methods in Korea—Impact on Energy Use and Greenhouse Gas Emissions Hyunji Im and Yunsoung Kim *Energies* 2020. [www.mdpi.com/journal/energies](http://www.mdpi.com/journal/energies).

<sup>4</sup> E cooking Burundi from the UN World Food Programme

### *Clean cooking in Nigeria*

In Nigeria, the use of firewood and charcoal for cooking is still common but efforts are being made to reduce it. Kerosene remains a common fuel for cooking. The target set in the UNFCCC Nationally determined contributions (NDC) is for 48% of households to use liquefied petroleum gas (LPG) and 13% to use improved cookstoves by 2030.

The NDC also aim to provide off-grid and solar mini-grid to 5 million households or 25 million people by 2030. Developing cheap solar systems may allow electricity to be more generally used for cooking.

The new data-driven interactive Nigeria Integrated Energy Planning Tool, launched in February 2022 by the Federal Government of Nigeria, will play a vital role in helping Nigeria achieve its shared energy access by 2030 alongside energy transition Net Zero goals by 2060. The energy planning tool is powered by extensive geospatial modelling and layers of data. It offers critical data and analysis that would assist the country in achieving universal access targets for both electrification and clean cooking. The interactive platform will provide actionable intelligence for the Government and private sector stakeholders to deliver least-cost access to electricity and clean cooking in Nigeria.

## **2.3. Buildings' energy flexibility**

In traditional electric power systems, since there is no or limited storage possibility (only through pump storage of water), the power-demand equilibrium has to be managed carefully to avoid excess of demand or surplus of production.

The idea of adapting as much as possible demand to the available production leads to the concept of demand flexibility, especially to shave peak loads or shift loads that may be anticipated or postponed when a lot of power is available.

This has been done for many countries through contracts between the electric utility and some industrial facilities able to interrupt their process. For residential customers, it has been already done in some countries as France did in the 1950s by remotely controlling electric water heaters: customers allowed the network operator to switch on/off their water heaters – technically, the operator sent a signal to the heater through the electric network, a Power Line Current (PLC) – in exchange of which the customer paid lower tariffs. This allows the French electric Utility EDF for example to shift load at night when demand is lower. Another possibility, used in different countries, was tariff modulation (seasonal, day/night, cold periods, etc.) to incentivise customers to use some equipment like washing machines when electricity is cheaper.

In the electricity system of the future, renewable power with volatility and non-adjustable characteristics will play a major role in power supply. Therefore, buildings should be able to achieve better flexible electricity use by consuming renewable power from their own photovoltaic power system and their other eventual low-carbon source of electricity (wind, etc.). They would then contribute to the optimisation of the electric power system. Furthermore, if the building is less dependent from the power grid, it possesses higher resiliency to any power grid problems.

Since the 1950s, new technologies have appeared and are increasingly deployable at affordable costs in many countries. Three ground-breaking technologies are indicated below.

- Information and communication technology, internet, Internet of Things (IoT), 'smart-meters' (which are one application of IoT) – all these provide new possibilities for the control, distant or not, of home and office equipment.
- Energy storage systems in buildings – this mainly refers to fixed batteries or electric vehicle batteries. Here, electric vehicles will support two-way charging and discharging, which will not only meet the electric vehicle attributes but also become an effective approach of regulating electricity through one more contribution of the end user.

- Contrary to traditional power electric systems and end users' appliances, more and more equipment and appliances use or provide Direct Current (DC), instead of Alternating Current (AC). The latter was historically developed to produce both low voltage for the end users for safety reasons and high voltage at the plants for economic reasons. Examples of DC systems include: LED lamps, the batteries of our mobile phones our remote controls, batteries in general, PV panels, etc.

All such technologies may contribute in different ways and in many different combinations to increasing flexibility in buildings, allowing the development of new business models and, above all, reduce GHG emissions. An example of how all these technologies are integrated into the low-carbon shift in the building sector in China is provided in the box below<sup>5</sup>.

#### *PEDF buildings: the Chinese low-carbon approach in the buildings sector, Part 1*

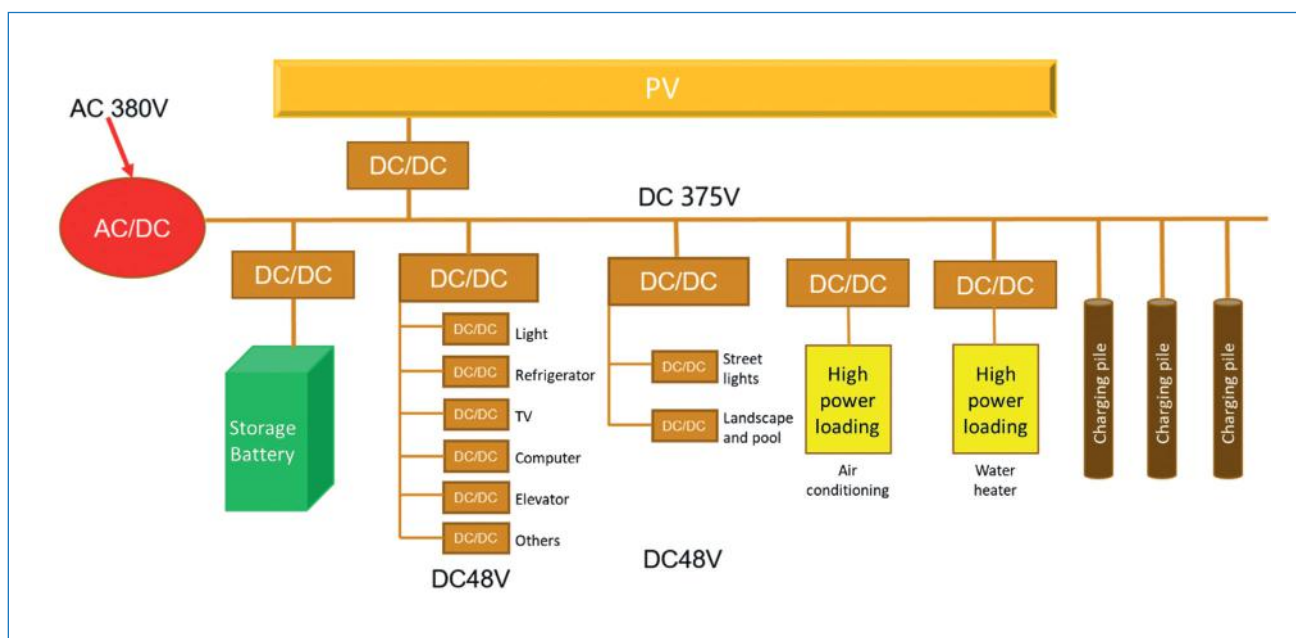
The Photovoltaic, Energy Storage, Direct current, Flexibility (PEDF) building integrates technologies to adjust real-time, as best as possible, the balance between local power supply and power demand. PEDF buildings are thus able to contribute to power system carbon neutrality.

Taking into account the increasing importance of appliances using DC, the electric distribution network of such buildings uses DC and not AC. This is also allowed by the advancement of electrotechnics and electronics.

To give an order of magnitude, every 10 000 m<sup>2</sup> of PEDF office buildings is estimated to be combined with 100 smart charging piles and electric vehicles (EVs) and may supply 1 MW of flexibility capacity and 5 MWh power storage capacity. Every 10 000 m<sup>2</sup> of residential buildings is estimated to be combined with 100 smart charging piles and EVs may supply 0.5 MW flexibility capacity and 5 MWh power storage capacity.

The Figure below shows an example of the energy distribution with all usual uses in a PEDF building.

For more details, see for example <https://iea.blob.core.windows.net>



**Fig. 2.5.** Example of PEDF buildings power system in China

<sup>5</sup> Yi Jiang. PSDF (photovoltaic, storage, DC, flexible)—A new type of building power distribution system for zero carbon power system [J]. Heating Ventilating & Air Conditioning, 2021, 51(10): 1-12(in Chinese).

*The PEDF building in China, Part 2.*

A set of pilot PEDF buildings are already built in China, for example the IBR Future Complex. The IBR Future Complex in Shenzhen is a 6259 m<sup>2</sup> 8-floor office and research building, located in a hot summer and warm winter climate zone in China, and designed for net zero energy with very low energy demand. The building is also the first one using 100% Direct Current (DC) power distribution to provide electricity for all its end use demand. The IBR Future Complex only connects with the utility AC grid through two 100 kW AC/DC converters, while its peak power demand can reach 345kW. Another focus is on the use of DC power to electrify building end use appliances, in which both the office and residential scenarios are developed. The IBR Future Complex was completed in 2019, and several advantages of DC power system have been verified through two years of operation, such as better power safety, system efficiency, a grid-friendly and easy to control system, etc.

**2.4. Potential role of hydrogen in the buildings sector**

Hydrogen may play a role in the decarbonisation of buildings probably limited to two types of uses.

At present, during the construction phase, equipment that cannot be connected to the grid is powered by diesel engines. In the future, these will be replaced by battery electric equipment in the case of small machines with a low to moderate energy demand, and by low-carbon hydrogen powered equipment (internal combustion engines or fuel cells) when power consumption is large or continuous and if hydrogen is available at reasonable price. Many construction equipment suppliers are now developing such alternatives (JCB, Liebherr, Sany, etc.). The advantages of the hydrogen solution are the elimination of the carbon footprint during the construction phase as well as a significant reduction in the noise level, an important requirement in urban environments.

In normal operation, a building is connected to the grid and hydrogen has no specific role to play there. However, in case of long-lasting power failure (due to extreme events), hydrogen can be used to provide emergency power, thus replacing diesel gensets. Such an approach is already applied to some large buildings (office towers, hospitals, data centres, etc.).

**3. Decarbonisation of urban energy supply systems****3.1. Low-carbon heating district networks****3.1.1. Various district heating and cooling systems**

Many different types of district heating and cooling systems already exist, some providing heating and cooling at the same time, even though heating systems are far more widespread. A great variety of structures make it possible to adapt to local conditions: only one heating source or multiple heating sources, heat storage tanks, a temperature setting imposed by the source or adjusted to the needs through heat pumps at the entry of the buildings, digitalised management systems, etc. More and more of these networks are low temperature (0 - 40 °C) since it may be sufficient for correctly insulated buildings and/or to allow increased efficiency and limited losses.

Depending on the energy sources, the CO<sub>2</sub> content of the kWh provided to the users may be very different. The networks may benefit from local waste, excess industrial energy, geothermal energy, thermal panels and also PV panels and batteries. The operators are progressively using more and more such resources even if traditional solutions (the use of coal, gas, cogeneration of thermal plants) are still used.

**3.1.2. Low temperature heat sources***(1) Industrial waste heat*

Industrial waste heat is an important kind of waste heat source. At present, including metal smelting, cement production, the chemical industry and the production of building materials still implies large amounts of waste heat that have not been utilised. The temperature of such waste heat is in the range of 30 °C to 200 °C, which is difficult to recycle for industrial production process. If this heat is recovered to heat a city, it may cover all or

a part of the heating need of the city. Using such waste heat is evidently positive as it avoids other emissions. This heat used by the city may be considered as “zero-carbon” heat since no emissions are produced for its use (or low-carbon if taking in account the initial emissions to build the recovery system to be precise). Even if industrial processes are transformed in a carbon-neutral future, there will still be a large amount of industrial waste heat to be used.

According to statistics and projections, China for example, following its low-carbon transformation of its industrial generation process as foreseen, still consume about 660 million tonnes coal equivalent (TCE) of fossil fuels and 3 600 TWh of electricity. Part of such energy consumption will eventually be released into the environment in the form of waste heat, which can be utilised for district heating.

In addition to traditional industries, some emerging industries, such as data centres, will also generate waste heat. In China, for example, the rapid development of data centres has also led to a rapid increase in power consumption by the cooling system of the computer room resulting in the availability of low temperature waste heat, above 40 °C generally. This kind of waste heat is generated in centralised locations and easy to be collected. It is predicted that the residual heat emitted by data centres in China could reach some 360 TWh per year in the future.

## *(2) Biomass and waste*

Biomass mainly comes from agricultural and forestry wastes. Straw of various crops and manure from the livestock industry can be collected and processed as fuel (e.g. straw compression block, biomass natural gas, biomass methanol, etc.). These biomass fuels can be used to replace the fossil fuels of the above-mentioned thermal power plants and reduce CO<sub>2</sub> emissions, even though burning does induce CO<sub>2</sub> emissions.

In addition, urban waste incineration cogeneration plants provide low-carbon electricity for cities, as well as low-carbon heat. For example, it is a normal feedstock for district heating networks in Sweden and most countries of Northern Europe and is increasingly so worldwide.

Buildings, both commercial and residential, produce a great amount of organic and inorganic residues. These are collected and then either recycled (inorganic) or disposed of in landfills where they decompose, producing methane (CH<sub>4</sub>) and CO<sub>2</sub>. This process may result in wasteland areas and the generation of GHG.

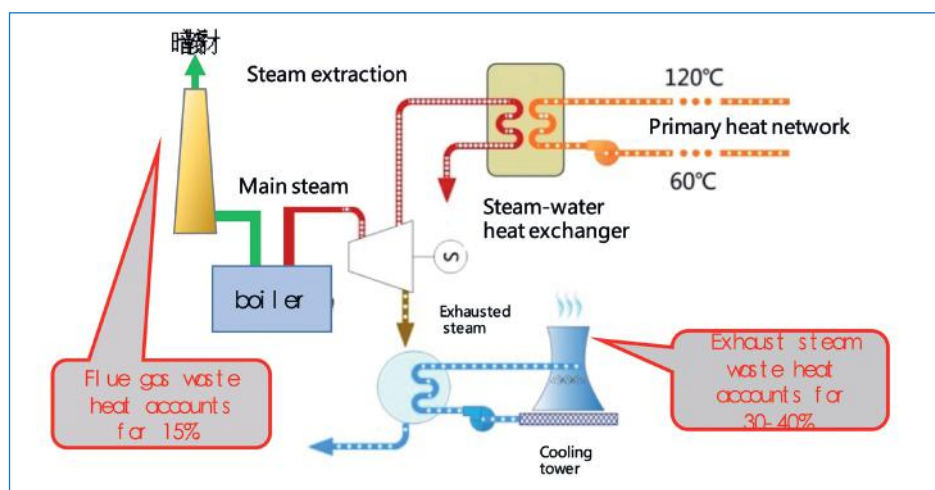
Technology exists that could make much better use of organic waste, in buildings or specific waste processing installations, by capturing CO<sub>2</sub> and CH<sub>4</sub> and thus producing energy and other by-products as well as compost.

Commercial equipment also exists, by which food products are bio-digested to generate compost. It is now used in some restaurants and sports stadiums, where tonnes of food waste are generated daily. Similar products could be used in residential buildings and shopping malls, for example.

An upgrade in these bio-digesters could be the use of sludge, which is now dumped into the sewer, to capture CH<sub>4</sub> and CO<sub>2</sub>, otherwise uncontrollably produced in the sewer. The former may be combined with natural gas or LPG used as a domestic or commercial energy source. In some cases, CO<sub>2</sub> may be used to produce carbonic acid or filtered through dense greenery, for example.

## *(3) Waste heat recovery from power plants*

Thermal power plants, including pure condensation power plants and cogenerations, exhaust large amounts of waste heat through steam and flue gas, as shown in *Fig. 2.6.*. In a large coal-fired cogeneration plant, the waste heat from the exhaust steam accounts for over 30% while waste heat in the flue gas exceeds 15% of the input heat supply. And for a pure condensation plant, the waste heat produced from exhaust steam accounts for over 50% of the input heat supply. Generally, heat networks sourced by a power plant operate at ‘high’ temperature (over 60 °C).



**Fig 2.6.** Potential waste heat recovery in thermal power plants (from Building energy research center of Tsinghua University, 2019 Annual report on China building energy efficiency, Beijing, China Architecture & Building Press, 2019 (in Chinese).)

In some countries, in the future context of a carbon-neutral power system, a certain number of thermal power plants using biomass or with CCS may possibly be retained in the power system to meet some seasonal power gaps. Such gaps may stem from the fact that photovoltaic and hydroelectric power generation capacity is much higher in the summer than in winter. In such a case, using the waste heat of such plants should be considered.

In China for example, retained thermal power plants could generate approximately 1 500 TWh of electricity annually, representing approximately 11% of total future electricity consumption. The waste heat resulting from power generation would provide cities with zero-carbon heating and meet the heating needs of approximately 12 billion m<sup>2</sup> of buildings space, which accounts for about 60% of the total heating area in northern China.

Nuclear power plants are another source of waste heat. For example, a 1 000 MW nuclear power plant can provide about 1800 MW of waste heat. Furthermore, the operating time of nuclear power plants is almost twice that of normal thermal power plants, and the quantity of waste heat exhausted from a 1 000 MW plant is about 13 TWh throughout a year.

In general, it is only possible to use such waste heat, from a technical and economic point of view, if it is decided when the plants is built.

### 3.1.3. Seasonal heat storage

Heat, as mentioned above is called waste heat when it is produced by other production processes. This means that waste heat fluctuates with the production process. This creates time mismatches between heat generation and heat demand. For example, power plants, factories and data centres generate waste heat all year round, while heat is needed mainly in the winter: heat produced in other seasons is not fully utilised, which results in wasting such valuable heat. In addition, in China, for example, when the Spring Festival comes, factories close and electricity consumption is greatly reduced, as is, subsequently, waste heat from these power plants and factories, thus causing heat shortages. In order to achieve the matching of waste heat supply and demand, seasonal heat storage may be an efficient solution to solve the problem of inconsistent heat demand and generation time.

In addition, seasonal heat storage can also play a role in the regulation of the peak heat load. Through the instantaneous release of a large amount of stored heat, the heating capacity can be greatly increased in the short term to bear the peak heat load.

### 3.1.4. Temperature converters based on heat pumps

In a district heating system dominated by low grade waste heat, the temperature of all kinds of heat sources varies from 0 °C to 200 °C. At the same time, the temperatures customers require may be very different: they depend upon the form of heat dissipation terminal, building insulation, courtyard pipe network, etc. Heat temperature needs to be adjusted as it is collected and delivered to the user. Necessary temperature adaptations may be made by heat pumps.

### 3.1.5. Long-distance heat transportation

Another problem in using large-scale waste heat is the mismatch between waste heat sources and heating demands in spatial distribution. Figuring out to transport heat economically over such long distances is the challenge.

The application of the above-mentioned temperature converter can greatly reduce the backwater temperature of the heat network, and change the supply and return water temperature of the heat network from 130 °C/70 °C to 130 °C/10 °C. The difference between the temperature of the water supply and the temperature of the backwater nearly doubles the amount of heat that can be transported by the same network, dramatically reducing the cost of heat transfer. Furthermore, the reduced return water temperature of the heat network can greatly improve the energy efficiency of the waste heat recovery system at the heat source, thus further reducing heating cost. The economic heating radius is about 80 km compared to coal-fired boiler heating systems and 240 km compared to gas-fired boiler heating systems, as Fig 2.7. shows.

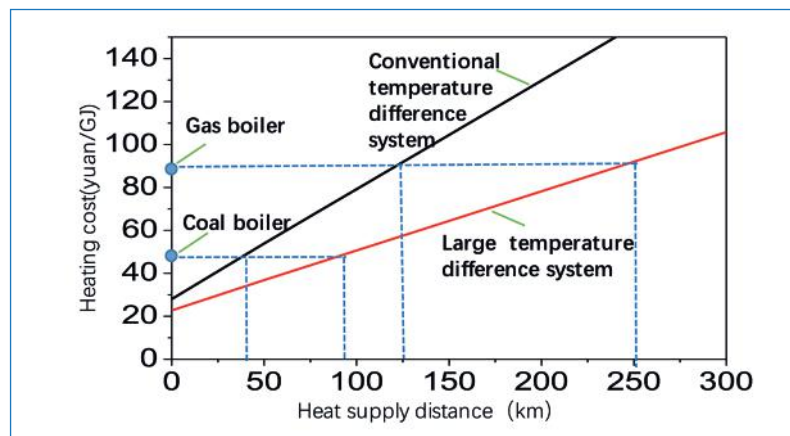


Fig 2.7. Costs of conventional heating systems and large temperature difference heating systems for large heat supply distances

## 3.2. Potential role of hydrogen for cities and communities

In several countries with sparse population, such as Canada and Australia, isolated communities are not connected to the electric transmission or distribution grid. They generate their own electricity, most of the time using a thermal power plant fed by heavy fuel oil. Not only does this generate a significant amount of CO<sub>2</sub> and other atmospheric contaminants, but the operating costs of the power plants is also very high as the fuel has to be imported from far away (in Northern Canada by shipping during the summer season). In these communities, the price of electricity can reach 1.5 CAD/kWh, as compared to an average of 0.1 CAD/kWh in the populated areas of Canada. The solution to decarbonise the communities is to use renewable energy as a source of local power and dimension the system to convert part of the unused power into hydrogen for long-term storage and further use when the renewable sources cannot inject enough power in the local grid. It should be noted that the use of hydrogen to power isolated communities has been tested in the Raglan mining complex of Glencore in Nunavik.

## 3.3. Smart Cities

### 3.3.1. Introduction to Smart Cities

The concept of 'smart city' is not very precise but the basic objective is to meet the demands of the urban population in a sustainable way to improve lives and provide greater efficiencies in delivering services. It often includes some technologically advanced choices. Core infrastructure elements in smart cities are: adequate water supply; assured electricity supply; sanitation; solid waste management; efficient urban mobility and public transport; affordable housing; robust IT connectivity and use of Internet of Things; e-governance; citizen participation; sustainable environment; the safety and security of citizens; health and education.

In many countries, cities and urban areas are being planned with the same broad objective but under different names: sustainable cities, Net Zero cities, solar cities, BiodiverCities, etc.

### 3.3.2. Cities in the world: current situation

The majority of the world population is now urban. The urban population of the world has grown rapidly, from 751 million in 1950 to 4.46 billion in 2021. The percentage of population that lives in urban areas is thus 56.6% of the world population. It is projected that by 2050, 68% of the world population will live in urban areas<sup>6</sup>. The pace of urbanisation is projected to be faster in developing economies. It has been widely recognised that the growth of urbanisation has taken place at the expense of climate and nature. It is estimated that cities and metropolitan areas are responsible for about 60% of global GDP and 70% of global carbon emissions. For the purpose of decarbonisation, cities are, therefore, a front runner for consideration.

### 3.3.3. Challenges for cities to become smart

Buildings are major constituents of cities. The buildings sector is not only a major consumer of energy and water but is also responsible for transportation and communication requirements, and is majorly responsible for the urban congestion on traffic and business, government infrastructure, educational institutions and health facilities. The siting of buildings, their design, neighbourhood planning and overall town planning can bring a drastic change in the environmental consequences of an urban conglomeration. This also provides a major opportunity for the decarbonisation of cities basically through the decarbonisation of buildings and related infrastructure such as roads, transportation, offices, industry, marketplaces, education & health facilities, recreational facilities, communication, etc. Waste utilisation and use of green energy can contribute to sustainability. Smart cities, therefore, occupy an important space in building decarbonisation. However, one of the major considerations in this decarbonisation initiative is how a city is formed. Cities have historically evolved to provide adequate opportunities for production and consumption models of sustainable economies. As urbanisation advances, the up to now ever-increasing requirements of office buildings - which could change with the post-covid and climate change induced increase of remote work - residential housing, markets, spaces for education, health care, recreation and for so many related facilities, thus need to be addressed. It could be the same for the stores and shopping centers with the development of the E-commerce.

Several countries and cities have developed strategies and applications to support urban green infrastructures and nature-based solutions (NBSs). Building yards and surrounding areas can be an important part of the urban green growth and contribute to reducing the need for cooling. Carbon-binding capacity and storage are directly dependent on the leaf area and biomass of a plant, and thus on the different vegetation types. Depending on the local climate, guidelines for planting appropriate plants can help substantial carbon sequestration and storage (CSS) potential. Furthermore, the adaptation and optimisation of the technologies to different climate zones is a very important issue.

### 3.3.4. Existing, forthcoming and possible breakthrough solutions for smart cities

With new technological breakthroughs, global societies are undergoing major changes to make everyday lives better, more efficient and more eco-friendly. Nevertheless, a number of efficient technologies and solutions are now available that can address key issues such as healthcare, transportation, and water and energy management in a city.

Information and communication technologies, with the Internet of Things (IOT), Big Data and Machine Learning, allow the development of 'platforms' that play a crucial role in improving the efficiency of transportation networks, delivering real-time information to users and providers, bringing down fuel consumption and related carbon emissions. As a result of improved efficiency, transportation becomes then affordable to all the inhabitants of the city facilitating an inclusive approach.

As a tool for action and an instrument to improve the lives of all citizens, the International Institute for Management development in Lausanne, Switzerland (IMD) and Singapore University of Technology and Design (SUTD) recently brought out the third edition of their Smart City Index (SCI). The *Smart City Index Report 2021* includes 118 cities of the world. In this report, the 'smart city' continues to be defined as an urban setting that applies technology to enhance the benefits and diminish the shortcomings of urbanisation for its citizens. Data collected for the survey included five key areas: health and safety, mobility, activities, opportunities, and governance.

This edition of the SCI ranks the cities worldwide by capturing the perceptions of residents in each city. The

<sup>6</sup> World urban population 2021-StatisticsTimes.com

final score for each city is computed by using the perceptions of the last three years of the survey.

The Top 10 smartest cities in 2021 were: Singapore (1<sup>st</sup>), Zurich (2<sup>nd</sup>), Oslo (3<sup>rd</sup>), Taipei City (4<sup>th</sup>), Lausanne (5<sup>th</sup>), Helsinki (6<sup>th</sup>), Copenhagen (7<sup>th</sup>), Geneva (8<sup>th</sup>), Auckland (9<sup>th</sup>) and Bilbao (10<sup>th</sup>).

The report emphasised that, in order to unleash the full potential of smart cities, a necessary balance should be found between the technological aspects of smart cities and their human aspects. However, apart from these 118 cities reported by the third edition of the *Smart City Index Report*, there are many more cities, both big and small all over the world, that strive for improving their urban infrastructures, taking several steps that include technological developments, sustainability goals, and the aspiration of the inhabitants in the same way as smart cities try to do. The example of India is presented below.

#### *Examples of smart cities in India*

It is estimated that India's buildings stock is set to grow by 0.86 billion square meters by 2030. This is an opportunity to plan and build only Green Cities.

In 2014 the Government of India announced its ambitious plan to build smart cities across the country on building new smart cities and redeveloping existing urban regions with population of over 100 000 people. The national Smart Cities Mission of the Government of India (<https://smartcities.gov.in/>) is an urban renewal and retrofitting programme with the mission to develop smart cities across the country.

100 smart cities will soon be a game changer and usher in a paradigm shift in the way cities are conceived and designed.

Green cities and smart cities go together, and the former is an integral part of the latter. Focus areas of green cities are: employment opportunities; walking distance to work; the treatment and use of waste water; open spaces and green covers; and stakeholder participation.

India is one of the first few countries to develop an exclusive rating system for Green Cities through the Indian Green Building Council (<https://igbc.in>). IGBC Green Cities Rating, as standards for the greening of such large developments, based on sound environmental principles, has been launched since 2015. IGBC is closely working with Development Authorities and Developers to apply green concepts and planning principles in several Indian Cities, resulting in reduced environmental impacts that are measurable, thus improving the overall quality of life.

## 4. Sustainability, public policies and regulation

Energy policies are relying on sticks, tambourines, and carrots. In the context of the decarbonisation of the buildings sector:

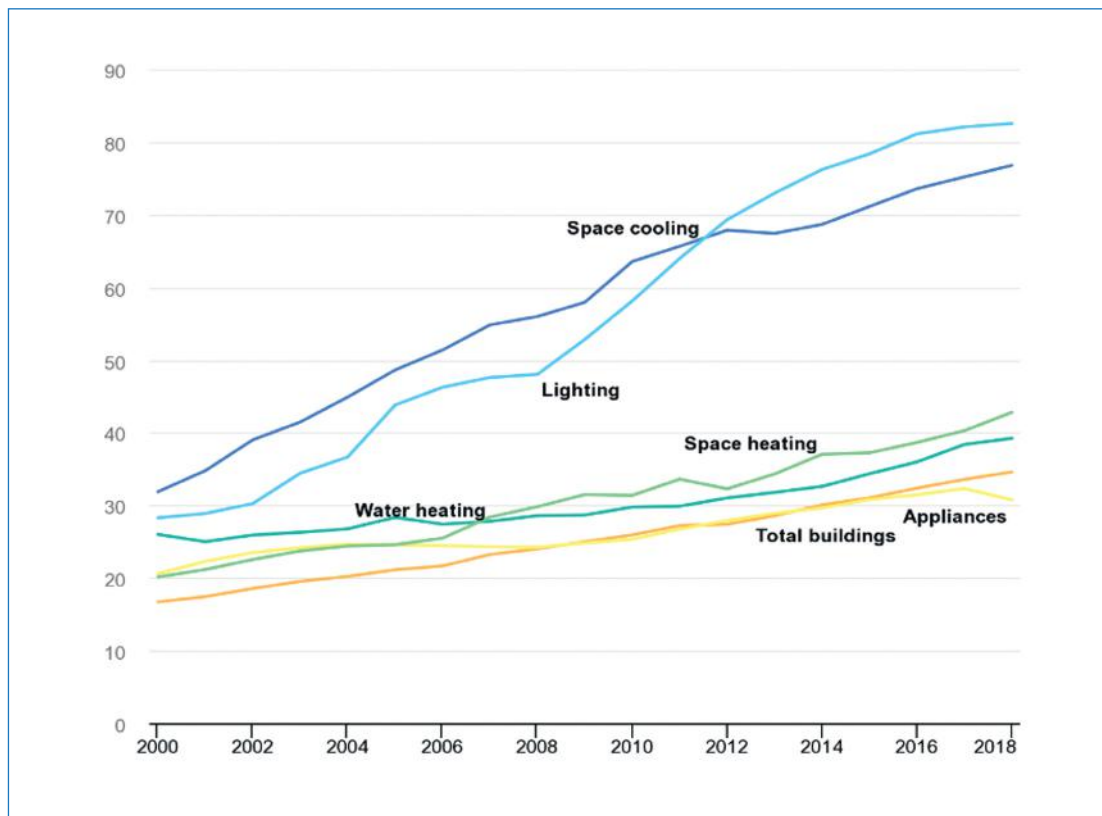
- i) Sticks are regulations, codes and performance standards that provide benchmarking metrics and indices of how the performances of buildings and their energy end users conform to legal requirements. For buildings, stick policies include: building design codes to implement passive design measures and decrease building heating and cooling demand, for both new constructed buildings and the retrofitting of existing buildings; minimum energy performance standards for building systems and appliances, such as the Minimum Energy Performance Standard (MEPS) for appliances and lightings. These stick policies are normally mandatory and well implemented and contribute to a significant effect on building energy conservation and emission reduction.
- ii) Tambourines are information tools such as capacity building, labelling, and awareness-raising campaigns that inform and educate the public on compliance requirements, decarbonisation pathways and energy saving strategies. Building Labels and Energy Performance Certificates (EPCs), energy audits and information disclosure (especially for government buildings), as well as appliance labelling and information campaigns, are proven and effective policy tools in the building sector. Building energy consumption feedback with smart meters is also an information instrument exploited to reduce the energy use of buildings. In the context of carbon emission reduction, real-time signals of emission factors of electricity are useful to nudge the behaviours of the occupants, in order to implement demand-side response and achieve emission reduction. The digitalisation trend in the building and power sectors provides opportunities for the application of carbon emission information tools.
- iii) Carrots are economic incentives such as rebates and subsidies to encourage outstanding building performance through either technological innovation or curtailment practices. Grants and subsidies are traditional financing instruments in the building sector. They are widely used by governments all over the world, for instance to improve the energy performance of new buildings or appliances and the retrofitting of existing buildings. Towards the target of renewable energy on-site generation and utilisation, several subsidy tools have been implemented, including direct investments, feed-in tariffs, etc. Proper subsidies and electricity pricing scheme designs with carbon signals are key to motivate on-site power generation and build flexible energy demand. In addition, new business models – often based on the internet, and more and more also on AI – can as well contribute to bolster behaviours and energy efficiency.

Buildings policy tools are often integrated and coupled: such consistency is important to facilitate the decisions and actions of the numerous stakeholders. Furthermore, it is decisive that they facilitate:

- the reduction of GHG emissions at the lowest possible cost in the area of concern;
- decision-making and the rapid implementation of change, taking into account potential conflicting interests of owners and users in particular.

The number of countries implementing standards and labels on the equipment of buildings is increasing, especially in the area of lighting (with LED and LED management systems) and cooling which are in rapid development in most countries.

Much information on the progressions of standards and labels is available in the GABC reports. *Fig. 2.8.* below, from the GABC 2020 report. This shows the percentage of the world population ‘benefiting’ from standards and labels for the different uses in the buildings.



**Fig. 2.8.** Percentage of the world population benefiting from a standard or a label by energy useChina building policies, a case study

**Source:** Policy coverage of total final energy consumption in buildings, 2000-2018 - Last updated 26 Oct 2022

<https://www.iea.org/data-and-statistics/charts/policy-coverage-of-total-final-energy-consumption-in-buildings-2000-2018>

*The Chinese government has instituted new policies to promote buildings' energy conservation.*

Such a national buildings' energy conservation plan was updated every five years to illustrate the main target and key measures of buildings' energy conservation measures. For example, the 13th Five-Year Plan for Building Energy Conservation and Green Building established a set of targets including energy efficiency improvement, a proportion of green building' in new constructed buildings, green building material applications, the retrofitting of existing buildings, etc. Effective policy tools for implementing the Five Years National Energy Plan are standard improvement and implementation among both new and existing buildings. A series of energy conservation standards for buildings took effect in recent years, including the energy efficiency design standards for public and residential buildings in several cold zones, in hot summer and cold winter zones and in hot summer and warm winter zones. Economic incentives integrated with the Minimum energy performance standard (MEPS) were also implemented in China, and significantly improved the ownership of energy efficient home appliances and home lighting bulbs.

Towards China's carbon neutrality, a series of action plans and new policy clusters are also being launched. The Carbon Peaking Action Plan by 2030 which was launched in China identified several key areas of buildings' decarbonisation, including electrification, energy efficiency, PSDF buildings, zero carbon heating systems in northern China, and clean energy systems for rural China. Several policy measures and tools have been produced to support these key areas. For instance, both direct investment subsidies and feed-in tariffs have been used to promote distributed PV systems in rural China.

*Policy framework from South Africa, a case study*

South Africa has a reasonably well-developed policy framework, as well as public/private sector supporting initiatives.

The private property development sector has been a leader in pushing the sustainable building agenda forward, and in fact supported the establishment of the Green Building Council of South Africa (GBSA), which has developed and manages a number of Green Building rating tools. Such tools include existing and new buildings. The GBCSA has recently introduced a Net Zero rating tool which is awarded to buildings that show they have no ecological impact in one or more areas of water, energy, waste and ecology. To date, eight buildings have received Net Zero ratings.

At a government level, the national Department of Public Works and Infrastructure (DPW&I) has developed its Green Building Policy, which most Provincial Government Departments have also adopted and are applying to all new buildings.

A key element of government policy was the development of the South African National Standard SANS 10400XA Energy Usage in buildings, which all new buildings have to comply with. Through the DPW&I Green Building Policy, SANS 10400XA set an “energy trajectory” which will be incorporated into all future revisions of SANS 10400XA and which targets to achieve a reduction of 8% on previous maximum energy demand and maximum annual consumption every two years.

South Africa has also introduced mandatory requirements for public sector buildings greater than 1 000m<sup>2</sup> and private sector buildings greater than 2 000m<sup>2</sup> to publicly display Energy Performance Certificates (EPCs). The EPCs are based on actual energy usage over a period of one year, and are valid for a period of five years. The information contained within EPCs is being captured in a national database by the South African Energy Development Institute (SANEDI).

## 5. Education and training

### 5.1. Old and new needs toward low-carbon buildings

Energy transformation of buildings is a huge challenge, not only for R&D but also in education and professional development, in all related types of activities: from architects to engineers, from craftsmen to operators. Furthermore, traditional activities, like changing a window, are remaining and evolving, and new activities are in development like installing new technologies from heat pumps to smart metering. New expertise and capacity for craftsmen that install this equipment have to be built up.

With statutory requirements for climate protection and conserving resources constantly increasing, a holistic approach to recording, assessing and implementing efficiency measures is important. Aspects of ‘life cycle thinking’ and the circular economy, along with all relevant connections, methodologies and data, must increasingly and systematically be transmitted to multipliers in businesses via information and consulting networks for craftsmen and operators of buildings.

The quality of the realisation is also key as it has an impact on the energy needs, the level of emissions and the operation cost of a new building and after retrofitting. These questions on the quality of realization and related practices must certainly have a greater place in education and professional development.

Changing the windows of a building may not be economically profitable over a short depreciation period, even if the quality of the realization is good, but considering the entire life cycle and the attendant use of resources over a longer time frame, it may be a particularly sustainable solution. This example shows why improved continuing professional development must not be limited to technological aspects but explicitly include extended considerations of economic efficiency/profitability over a sufficiently long time. Such economic considerations should also include pricing in the side effects of new technological solutions.

In many European countries, about 1% of the buildings are modernised yearly; however, to reach the energy transformation goals, a threefold increase is necessary. It is then necessary to attract more young people in this area! It needs the mobilization of the entire ecosystem involved. For example, for many years, in Germany, the Learning Energy Efficiency Networks (LEEN), in a collaboration between businesses and academia (supported by public funding), have been assisting enterprises and housing associations in planning and implementing operational energy efficiency measures in buildings and processes. The focus is on measures that are relatively economically profitable from the point of view of the businesses.

## 5.2. Higher education

Sustainability and Life cycle analysis are already present today in some university disciplines, although often treated as a marginal topic. Life cycle design, on the other hand, is rarely taught other than in specialist courses. Both topics will play an increasingly important part in many disciplines, and not just in engineering, where it is of obvious relevance. An understanding of so-called ‘sustainable and life cycle thinking’ is also of importance in economics, business studies, sociology, political science, or the teaching professions, among others. This training can be given on specific topics such as energy efficient buildings.

Further, environmental impacts, aside manufactured homes, are increasingly shifting from the operating phase of buildings to the production phase, taking into consideration the energy intensive production of passive homes due to, for example, more energy and information technology or insulation material. In engineering, however, the focus is still on optimising and improving the operating phase. Therefore, in future, training in sustainability should become an integral part of any engineering degree. It is worth considering whether more mandatory practical work experience should be required at the beginning of an engineering course. This will help engineering students with their communication skills and provide an understanding of everyday practice in companies.

### *An example from Germany*

The transformation of the building energy supply requires expertise from engineering and architecture. Corresponding integrated Master courses at university level are either not available or not visible. An experiment at TU Munich showed the following challenges: formal hurdles for inter-faculty exams, different ways of teaching and learning. Architects prefer visualisation by drawings and pictures, engineers use formulas and graphs. It took a long time before the architecture and engineering students began to correspond. But the experiment was worthwhile: in the end, the students evaluated the lecture most positively and asked for more. Universities should establish common Master courses, or at least common lectures.

## 5.3. Training the future apprentices

Further skilled manufacturing workers/craftspeople able to find sustainable solutions and run the circular economy with the necessary technical knowledge of innovative processes are needed. In the coming decades, OECD countries will experience an increasing shortage of specialist workers in this field, due to the overvaluing of academic studies while the training of skilled workers and craftspeople is neglected – be it in installation and commissioning or maintenance and service. New technologies can only really be rolled out across the economy if the relevant craftspeople with relevant training are available.

From this viewpoint, a debate on the principles of the structure of education and training would doubtlessly be useful in many countries. It should again be discussed whether universities for applied sciences and apprenticeships in trades can be better interconnected. That is to say, whether very demanding trade apprenticeships should perhaps in future lead to a bachelor’s degree. This does not mean that the apprenticeship should become more theoretical – apprenticeship in a trade must remain very practical.

#### 5.4. Lifelong learning – Continuous Professional Development

As a result of rapid technological and social change, in the building sector like in others, lifelong learning is becoming more and more important at all levels of education and training, from trades through technical colleges to universities. Training and degree courses alongside work, in trades and at university, for continuing training in the aforementioned topics is becoming part of everyday working life. The specificity of the building sector compared to others is the high number of small and mid-sized local companies where continuous professional development may be difficult to organize.

While crossovers between trade apprenticeships, technical colleges and (technical) universities are becoming more transparent, this does not mean one-sided intellectual training!

Some more elements may be found in Working Group Circular Economy and Sustainable Energy, TU München, March 2022.

##### *India, a case study*

The building sector currently consumes 35% of the electricity generated in India. It is thus imperative that city development and planning should become integrated with sustainable, climate sensitive and resource preserving solutions from the construction industry. The Bureau of Energy Efficiency (BEE) developed the Energy Conservation Building Code (ECBC) and the Star-rating program for buildings to provide guidelines to the industry and encourage the construction of energy efficient buildings. To this end, a system that would provide the industry with the requisite pool of qualified professionals needs to be put in place. The current architectural education scenario in India, while able to meet the requirements of the industry, is not fully equipped to implement a national sustainable design and construction strategy. This would require fundamental and practical knowledge in building physics and climatology, passive solar design, energy-efficient technology and systems, state of the art computer simulation tools, and a broader understanding of the energy flows in the larger ecosystem. Moreover, with approximately 4 000 architects certified by the Council of Architecture (COA) in India each year, it is expected that there will be a growing shortage of architects to meet the demand for the construction of new buildings in the future. This challenge is further compounded by the fact that barely a handful of architecture institutions have significant focus on sustainable growth in the construction sector. An absence of up-to-date curricula as well as limited availability of trained faculty further aggravates the problem. To address these issues, Energy Conservation and Commercialization project Phase 3 (ECO-III) initiated an architectural curriculum enhancement initiative in India. The objective of the exercise is to assist academic institutes in preparing the next generation of architects and engineers who are aware of the needs of the Indian building design and construction industry from an energy efficiency and sustainability perspective. As part of this initiative, it is also proposed that the expertise and knowledge of the existing faculty will be upgraded by organising 'Train the Trainer' programmes as well as other programmes providing continuous learning opportunities. (Source: a need for curriculum enhancement in architectural education to promote sustainable built environment and mitigate climate change, USAID Energy Conservation and Commercialization Project Phase 3, October 2009).

## 6. Case Studies

### 6.1. Buildings' decarbonisation in Latin-America and impacts on regulation

77% of the population of Latin America and the Caribbean (LAC) countries (431 million total in 2021) live between the southern and northern tropics (Cancer and Capricorn), with a climate that is mostly between mild and warm, with medium to high humidity, as *Fig. 2.9.* shows, except for Monterrey, Ciudad Juárez and Tijuana in Mexico; Buenos Aires, Cordoba, Mendoza and Santa Fe in Argentina; Santiago de Chile in Chile; Montevideo in Uruguay; Porto Alegre in Brazil. All large urban areas are also in that area.

In consequence most of the energy used in buildings and households is applied to cooking, heating water, house appliances and cooling. Heating is not a widely used service.

With a relatively low GNP, LAC's population tends to consume less energy per capita than developed countries.

LAC's final consumption by energy and sectors for 2020 (OLADE, 2021), where residential takes 17.5% and commerce 5% of total energy consumption, reach 1240 TWh. This percentage has grown only 1% in the last 10 years.



*Fig. 2.9.* Latin-America geographical situation

As *Table 2.2.* shows, firewood is more used than other energy sources in Central America: it amounts to 78.8% of total residential energy consumption (140 TWh, 11.1% of LAC) and 27.8% of total firewood consumption in LAC.

Energy vectors	%
Natural gas	11.1%
LPG	18.3%
Firewood	24.1%
Electricity	42.3%
Other	4.1%

*Table 2.2.* Energy consumption by energy source in the residential and commercial sectors

Specific decarbonisation and energy savings initiatives in the residential and commercial sectors are being implemented in several Latin-American countries. Argentina, for example (De Schiller, 2020), has country-wide and regional tools to foster energy efficiency<sup>7</sup> in buildings, such as a non-mandatory standard for the energy capabilities of buildings and buildings' energy rating certification.

In Mexico, three main mechanisms to foster energy efficiency and sustainability are applicable, mostly in urban areas (Morillón G., 2015). One is the use of direct economic incentives, of which we can mention four examples:

- economic aid to exchange old inefficient refrigerators and washing machines for new energy-efficient models, as well as for solar water heaters;
- economic aid for the thermal retrofitting of buildings (thermal isolation and more efficient lighting and air conditioning);
- special mortgaging conditions for sustainable housing (designed for lower CO<sub>2</sub> footprint);
- bidirectional electrical energy interchange between buildings with photovoltaic generation and the distribution grid, as an incentive to this type of distributed generation.

Another mechanism is the publication of mandatory national standards for energy efficiency in new buildings and non-mandatory standards for construction materials, solar water heater systems and sustainable tourist building installations, among others.

The third mechanism is the certification and recognition of sustainable buildings and sustainable urban developments.

Other countries, like Brazil and Chile, have developed certification systems; however, no mandatory standards or legislation enforce their application (De Schiller, 2020).

Fig. 2.10. shows the changes in building' energy consumption from utilities (BECU) per urban inhabitant since the year 2000 for three countries (Argentina, Brazil, Mexico) and two regions (Central and South America). There seems to be a correlation between active measures to foster energy efficiency plus local sustainability in buildings, on the one hand, and BECU per-capita in urban areas on the other.

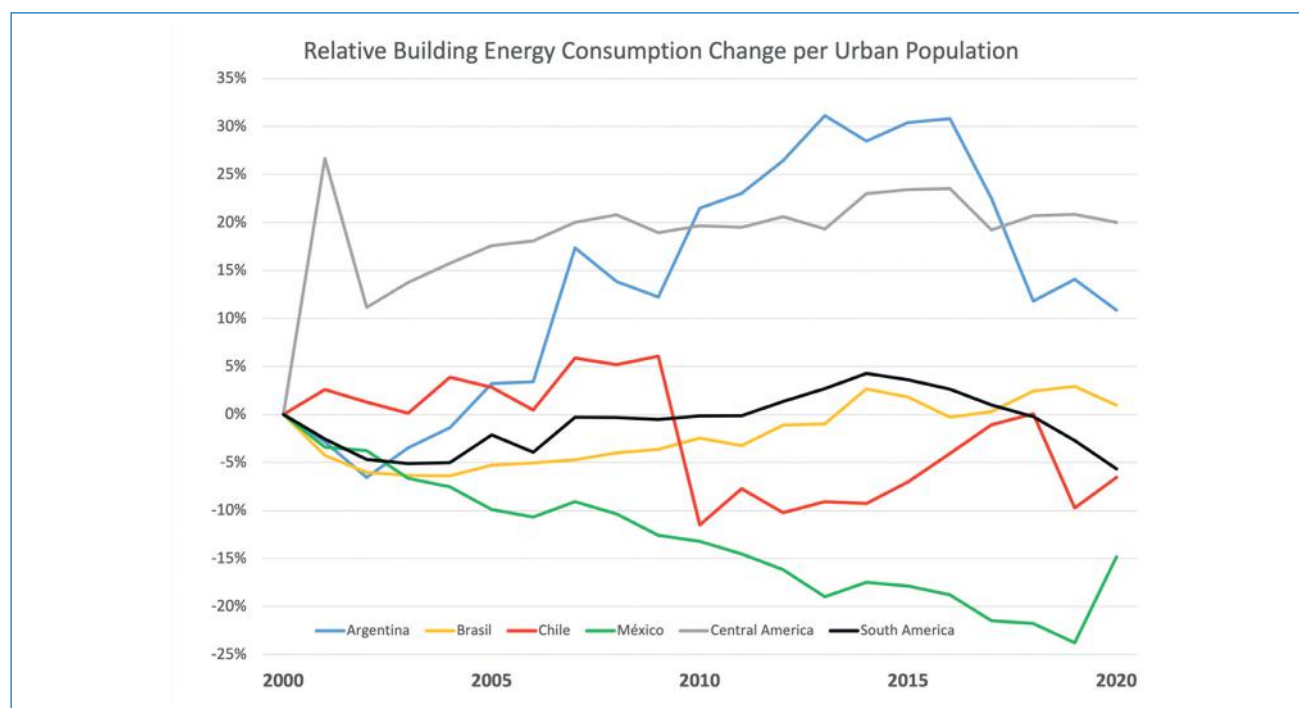


Fig. 2.10. Relative Building Energy Consumption from Utilities (BECU) change since 2000 per-capita in urban areas.

Source of data: PANORAMA ENERGÉTICO DE AMÉRICA LATINA Y EL CARIBE, 2021, OLADE, Organización Latinoamericana de Energía

<https://sielac.olade.org/WebForms/Reportes/VisorDocumentos.aspx?or=453&documentId=10000014>

OLADE is the Latin American Energy Organization" (in Spanish: "Organización Latinoamericana de Energía").

SIELAC is the Energy Information System for Latin America and the Caribbean.

<sup>7</sup> Energy efficiency has two prongs: one is the use of appliances that are more energy-efficient; the other is the substitution of energy supplied by electric and gas utilities by locally generated energy, mostly through solar heating and FV electric generation.

For Central America, even with a rapidly growing urban population, few decarbonisation measures have resulted in a 20% increase in BECU per-capita (urban) in 20 years. While, for Argentina, there was a marked tendency to lower BECU per capita (urban) between 2010 and 2020. Brazil's BECU per capita (urban) is almost unchanged, while South America as a whole shows a tendency to reduce BECU per capita (urban) after 2010, probably pulled by Argentina.

In Mexico's case, a continued reduction in BECU per capita (urban) is apparent and reached almost 20% in 20 years. Although direct economic incentives have been the primary drive to reduce BECU per capita, mandatory standards for energy efficiency in new buildings should maintain this tendency.

We can conclude that there is a clear opportunity to increase decarbonisation in buildings in Latin America, through incentives to promote local sustainability (reducing energy consumption from utilities) for both new and existing buildings<sup>8</sup>.

## 6.2. Decarbonisation at the district level: the case of poor neighbourhoods in developing countries

The scope of this case study is to analyse the consequences of the current system of subsidies in poor neighbourhoods in Buenos Aires (Argentina) from the point of view of GHG emissions and to propose another approach for decarbonisation and the improvement of the quality of life of inhabitants. This case study was carried out by the University of Buenos Aires in 2021.

We observe that in many countries:

1. households below the local poverty line have almost all their energy subsidised;
2. a percentage of the population receives partial subsidies;
3. the rest of the homes pay the total cost of energy.



**Fig. 2.11.** 'Villa 31' slum, located close to Buenos Aires downtown city.

Source: Google Earth

<sup>8</sup> The presentation of this case study is based on the following documents: De Schiller, S. e. (2020). Eficiencia Energética Edilicia en Argentina. Buenos Aires, Argentina: Centro de Investigación Hábitat y Energía.

Morillón G., D. G. (2015). Retos y oportunidades para la sustentabilidad energética en edificios de México: Consumo y uso final de energía en edificios residenciales, comerciales y de servicio (Vol. SID 689). Mexico City: Instituto de Ingeniería, UNAM.

OLADE. (2021, January 6). OLADE - Latin American Energy Organization. Retrieved 01 2021, from sielac.olade.org: <https://sielac.olade.org/WebForms/Reportes/InfogramaBalanceEnergeticoSimplificado.aspx?or=545&ss=2&v=3>

### Electricity consumption and subsidies in Buenos Aires slums

Around the 1930s, the first settlements were installed in Buenos Aires, as a result of its proximity to the port and the train terminals (see Fig. 2.11.). The expansion of the slums increased with the arrival of new immigrants from neighbouring countries. The territory in which they settle has been the fundamental issue for disputes since its establishment, generating organisational forms of resistance from the neighbours against the transfer or eradication projects. The situation of the slums is a complex problem from the social and urbanistic point of view. We will refer only to the present situation of the energy subsidies and their effects on GHG emissions.

The distribution of electricity in Buenos Aires is licensed to private companies. In the slums, homes do not have individual meters but community meters (see Fig. 2.12.) and all the consumption is paid from the federal and provincial budget.

As shown in Fig. 2.12., the electricity consumption by home in slums ranges between 2.5 to 3 times the mean consumption by home in the city of Buenos Aires. There are several possible reasons for this large difference: a) the condition of thermal isolation of the houses are worst in the slums; b) electrical appliances are less efficient there; c) heating is based on electricity (in most of the homes in Buenos Aires heating is based on natural gas); and d) as the electricity is free, there is no incentive to reduce consumption. This comment is not a criticism of the inhabitants of these areas, but an observation of the existing conditions in which they may use energy.

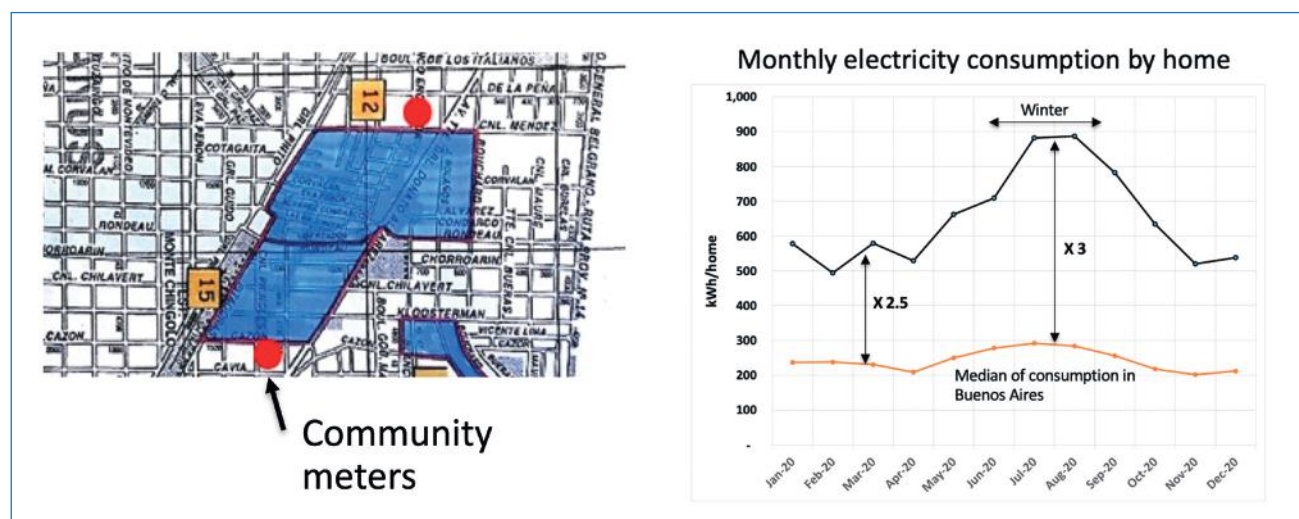


Fig. 2.12. Community meters in slums (left) and monthly electricity consumption by home in Buenos Aires vs. slums (right)

One of the two electricity distribution companies of Buenos Aires has, under this system, 68 000 houses that consumed 615 000 MWh in 2020, distributed in different slums of the metropolitan area of Buenos Aires. Considering a cost of electricity of USD 85/MWh and an emission factor for the electricity system in Argentina of 0.407 tonnes CO<sub>2</sub>/MWh, this means USD 52 million/yr of subsidies and 250 000 tonnes CO<sub>2</sub>/yr of emissions.

### Case study for one of the Buenos Aires slums

The following paragraph summarises the economic results of replacing subsidies to consumption by investment in energy efficiency, solar thermal and photovoltaic equipment, and district heating for 'Villa 31' in Buenos Aires City. 'Villa 31' has 7 950 houses with 26 400 inhabitants. 83% of the houses have clean water by pipeline, 47% of the houses have one storey and 36% have two.

The following analyses are calculated considering a cost of electricity at USD 85 /MWh, emission factor for electricity at 0.407 tonnes CO<sub>2</sub>/MWh, internal rate of return of 8% and prices in Buenos Aires. The slum is considered to be comprised of 8 000 houses.

- Efficient refrigerator

Considering the energy savings, the Net Present Value of the subsidies to consumption represents 55% of the cost of buying a new refrigerator. The new appliance would also avoid 0.274 tonnes CO<sub>2</sub>/yr of GHG by home and improve the quality of life of the inhabitants.

	Efficient Refrigerator with freezer
Description	To buy a A++ refrigerator replacing E class
Hyphotesis	Capacity: 409 liters      Service life: 15 years
Energy savings	673 kWh/year
Cost of Refrigerator	890 USD
NPV of Subsidies	490 USD
NPV/Cost	55 %
CO2 emission avoided	0.274 tonCO <sub>2</sub> /yr

- Solar thermal for hot water

Considering the energy savings, the Net Present Value of the subsidies to consumption represents 98% of the cost of buying and installing solar thermal equipment and a hot water tank. Such new equipment would also avoid 0.821 tonnes CO<sub>2</sub>/yr of GHG by home.

	Solar thermal for hot water
Description	To buy and install solar thermal and hot water tank
Hyphotesis	Capacity = 100 lts      Service life: 15 years Consumption = 160 lt/day
Energy savings	168 kWh/month
Cost of equipment	1500 USD
NPV of Subsidies	1467 USD
NVP/Cost	98 %
CO2 emission avoided	0.821 tonCO <sub>2</sub> /yr

- Solar photovoltaic.

Considering the energy savings, the Net Present Value of the subsidies to consumption represents 90% of the cost of buying and installing solar photovoltaic equipment. Such new equipment would also avoid 2.196 ton-CO<sub>2</sub>/yr of GHG by home.

	Solar photovoltaic on grid
Description	To buy and install a photovoltaic kit of 3.5 kW
Hyphotesis	Power: 3,5 kW      Service life: 20 years
Energy savings	5,396 kWh/year
Capacity Utilization Factor	0.176      Buenos Aires, 4.2 hr/day average
Cost of panels and install.	5,000 USD
NPV of Subsidies	4,503 USD
NPV/Cosgt	90 %
CO2 emission avoided	2.196 tonCO <sub>2</sub> /yr

- District heating

A 589 MW natural gas combined cycle power plant produces electricity in Buenos Aires at a distance of only 1 000 m from 'Villa 31' (see Fig. 2.13.). The heat generated by the power plant can be distributed through a system of insulated pipelines at very low cost. The hot water from the pipelines is used at houses for space and water heating. From the 168 kWh/month required by electric hot water tanks and the 353 kWh/month required for space heating as average during the 4 winter months, a total of 3 428 kWh/yr is replaced by the District System. Accounting by the 8 000 houses of the Villa 31, the Net Present Value of the replaced subsidies is USD 27 million. Although the cost of the project still must be assessed, it is estimated that it should reduce heating cost for the area. District heating would also avoid 11 160 tonnes CO<sub>2</sub>/yr of GHG.

	District Heating
Description	Space and water heating from heat generated in Combined Cycle Power Plant
Hypothesis	Natural Gas Power Plant 589 MW (Puerto Nuevo) . Distance = 1000 m
Energy savings/home	3,428 kWh/year
NPV of Subsidies/home	3,396 USD
NPV x 8,000 homes	27 MMUSD
Cost of District heating	To be computed
CO <sub>2</sub> emission avoided	11,160 tonCO <sub>2</sub> /yr

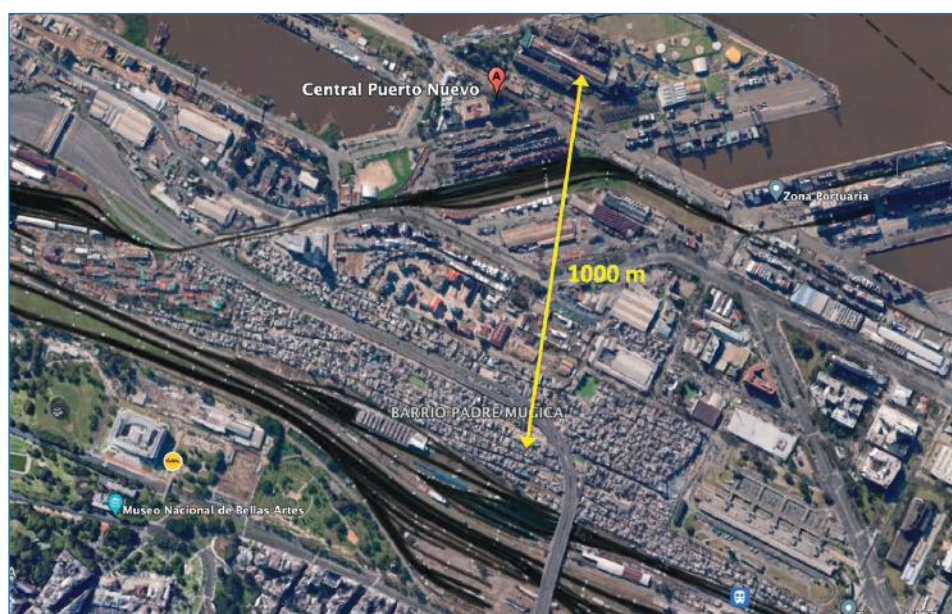


Fig. 2.13. Distance between the existing thermal power plant and the 'Villa 31' (Buenos Aires, Argentina)

Source: Google Earth

### Conclusions and key points of this case study

At present, electricity subsidies from the federal and provincial governments for an 8 000-home slum in Buenos Aires involve USD 6.1 million/yr. According to the factor emission of electricity in Argentina at the time of the study, GHG emissions resulting from the consumption of their inhabitants are 29 300 tonnes CO<sub>2</sub>/yr.

This study shows that replacing subsidies to consumption by one-time investment in solar thermal and solar photovoltaic residential equipment is practically 'neutral' from an economic point of view and would reduce GHG emissions by 24 134 tonnes CO<sub>2</sub>/yr (Table 2.3.).

Concerning heating, because a 589 MW power plant is producing electricity at only 1000 m of the site, with ‘waste’ heat available from the electricity generation process, district heating is one option for replacing subsidies to consumption in the case study of this paper. A combination of district heating for water and space heating and solar panels for electricity could reduce the present subsidies to USD 0.1 million/yr and GHG emissions to 570 tonnes CO<sub>2</sub>/yr.

It would be reasonable to install domiciliary meters for the small amount of electricity not covered by the solar panels, as an incentive to save energy and a tool in avoiding the use of free electricity for industrial activities.

For countries with financial problems, it may not be possible to afford such one-time investment that could replace subsidies to consumption with economic advantage and drastically reduce the GHG emissions produced in the slums.

	Investment	Subsidies Avoided	Net Present Value of Subsidies Avoided	CO <sub>2</sub> avoided
	MMUSD	MMUSD/yr	MMUSD	tonCO <sub>2</sub> /yr
<b>Efficient Refrigerator</b>	7.1	0.46	3.9	2 191
<b>Solar Thermal for hot water</b>	12.0	1.4	11.7	6 564
<b>Solar Photovoltaic</b>	40.0	3.7	36.0	17 570
<b>District heating</b>	To be computed	2.3	27.2	11 160
<b>Present Situation</b>		Present Subsidies MMUSD/yr		Present CO <sub>2</sub> tonCO <sub>2</sub> /yr
		6.1		29 300

**Table 2.3.** Subsidies and possible investments to replace them at the Buenos Aires slum (8 000 homes)  
MMUSD = Million US\$

### 6.3. Two case studies of district heat networks in China

#### *Project 1: Taigu long-distance heating project in Shanxi Taiyuan*

The Taigu heating project, presented in *Fig. 2.14.*, involves large temperature differences alongside a long-distance network. It was started in 2013 and successfully put into operation in 2016. This project was the first one in China to transmit waste heat from suburban power plants to the main urban heat network through long-distance pipelines with large temperature differences. The Gujiao Xingneng power plant is a large thermal power plant 40 km from Taiyuan city with a total installed electricity capacity of 3120 MWe and a thermal output of 4480 MWth. This power plant is used as the heat source for Taiyuan with a heating radius of 70 km. Four 1400 mm diameter transmission pipelines carry the hot water from the Gujiao power station to the intermediate energy station as the key part of the project. The main pipeline is 37.8 km long with 3 pumping stations and 1 emergency water make-up station. The six-stage circulating pump gradually pressurises the water. Height difference is 180 m. The design water flow rate of the long-distance heating network is 30 000 tonnes per hour with supply and return water temperatures of 130 °C and 30 °C. This system currently provides heat for 76 million m<sup>2</sup> in buildings with about 60% of the substations rebuilt with absorption heat exchangers with a return water temperature of 37 °C from the long-distance heat transmission network.



Fig. 2.14. General layout of the main heating pipeline from the Gujiao power plant to Taiyuan

The system provides significant environmental benefits. The cogeneration and industrial waste heat accounted for 79.2% of the total heat supply in Taiyuan. The district heating network kept expanding to replace small dispersed coal-fired boilers and meet the heating demand of new buildings. Since the implementation of the Gujiao long-distance waste heat transmission project in 2016, the system has replaced 41 million m<sup>2</sup> of heating by scattered coal-fired boilers, and the Taiyi power plant with 4×300 MWe units in the city centre has been shut down. Annually, the system replaces the use of 3.66 million tonnes of standard coal usage for heating and eliminates 13 000 tonnes of air pollutant emissions and 9.5 million tonnes CO<sub>2</sub> emissions by reducing the use of coal.

Because of the high efficiency of the heat source and the large reduction in the cost of heat transportation, the total heating cost of the long-distance heating system is also greatly reduced. The comprehensive heating cost of the Taigu heating project is about 138 yuan/MWh, which is similar to that of coal-fired boilers and much lower than that of gas-fired cogeneration.

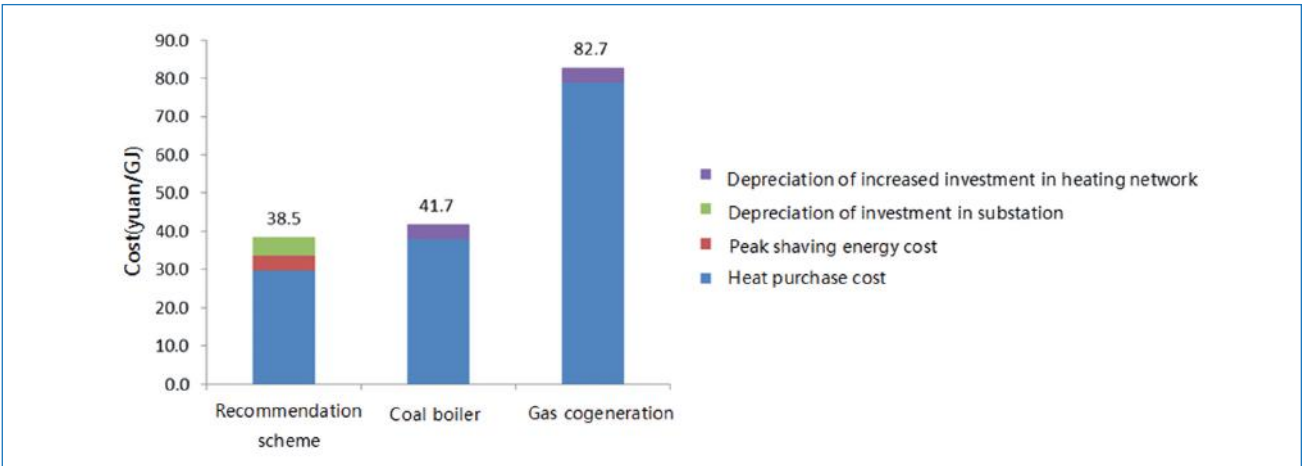


Fig. 2.15. Total heating cost comparison

### Project 2: Industrial waste excess recovery project from Qianxi steel factory in Hebei province

Jinxi Steel Plant and Wantong Steel Plant, hereafter referred to as Steel Plant J and W, are 10 kilometres to the northwest of Qianxi County. The annual steel production of Steel Plant J and W is about 6.5 million and 2 million tonnes respectively. The two plants purchase iron ore as raw material and produce steel products in four major processes: sintering, iron-making, steel-making, and steel-rolling.

Large amounts of low-grade industrial surplus heat is released during the production processes, and the heating potentials of blast furnace (BF) cooling water, blast furnace slag-flushing water, and low-pressure steam in power-generation devices are calculated in Table 2.4.. The maximum theoretical heating power is approximately 400 megawatts (MW).

Heat sources	Temperature (°C)	Quantity (MW)		
		Plant J	Plant W	Total
BF cooling water	35-45	116.80	39.90	156.70
BF slag-flushing water	<100	140.70	47.70	188.40
Low-pressure steam	143	44.00	8.00	52.00
Total		301.50	95.61	397.10

Table 2.4. Heating potential of industrial surplus heat in steel plants J and W

The district heating system in downtown Qianxi serves to heat about 3.2 million m<sup>2</sup> of buildings, and heat demand is about 150 MW. Considering the inner heat demand of Steel Plant J and W is 20 MW in sum, the total heat recovered is about 170 MW. Since the floor area of buildings in Qianxi keeps expanding rapidly, it is estimated that heat demand might reach 500 MW in 2030 or after.

A cascade heat recovery procedure has been designed, as shown in Fig. 2.16. The implementation of this project is divided into three stages with the growth of heat demand. So far, the first stage has been running for 8 years.

The total heat recovered in the 2020-2021 heating season was approximately 129 MW in average. The heating power of the slag-flushing water is about 90 MW. Comparing this part of low-grade surplus heat to heat from coal combustion with a thermal efficiency of 80%, the conserved fuel is equal to 40 000 tonnes of standard coal per year. Therefore, reductions in CO<sub>2</sub> emission, SO<sub>2</sub> emission, and NO<sub>x</sub> emission are some 106 000 tonnes, 340 tonnes, and 300 tonnes per year respectively.

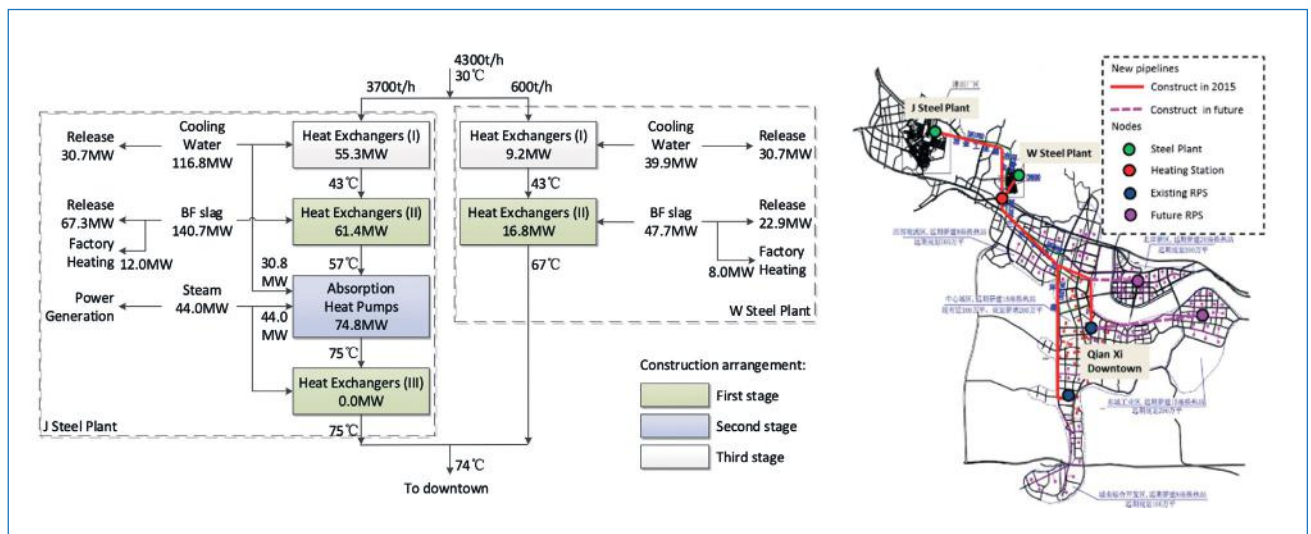


Fig 2.16. Heat recovery procedure and supply network

## 7. Key Messages and Recommendations

### Key Messages

1. A large number of technologies is available today, allowing us to act immediately on the decarbonisation of buildings. The following recommendations present our views towards this end. Most of them are 'no-regret strategies' and 'low-hanging fruit'. Some especially concern the existing building stock, since many of the existing buildings will still be present in 2050, while some other especially concern the new buildings.
2. Research and innovation is needed to enrich the already very significant number of technical solutions, giving then more possibilities to decrease the emissions.
3. Even if the direct use of solar waste heat has to be considered, we consider that the principal avenue for buildings decarbonisation is more and more electrification, as electricity will progressively have a lower carbon content.
4. We are fully aware that the situations are very different from one country to another, inside countries, etc. The solutions are not the same in industrialised countries and emerging ones. They are also not the same for favoured people and poor people for whom improving the quality of life comes first. In any case, the political, societal, economical and organisational dimensions are essential (see 1, 2, 3 and 9 especially).

### Recommendations

#### 7.1. Clear, stable, and holistic policies to effectively accelerate reduction in buildings' emissions

We recommend that all public policy projects impacting the building sector be only validated if they are oriented towards reducing emissions. This is not only about choosing energy vectors but also about the respective roles of the cities, the owners and the users in the decision process.

We thus highly recommend developing holistic public policies for the sector (codes, minimum energy performance standards, labels, financial incentives, taxes) and that they become even clearer and more stable in the long term. However, a review mechanism for improving such public policies should be incorporated and published.

We recommend paying attention to the implementation pathways of the policies through adapted indicators (specially the CO<sub>2</sub> emissions per m<sup>2</sup>). We also recommend conducting measurements after construction or retrofitting to check/audit final performances.

#### 7.2. Locally-adapted design, construction and equipment: keys to new sustainable buildings

We recommend trying to reach reasonable comfort with low emissions at affordable cost through this ordered list of priorities:

1. Best possible passive affordable design in the local climate and context, as it will bring down the annual cost of operation of the building throughout its lifetime.
2. Choosing the available low-carbon materials for building construction and energy sources/vectors: direct solar use (for water heating for example), geothermal heating or cooling, low-carbon heat from the district network, low-carbon electricity from local PV or from the network.
3. Choosing the most efficient equipment and building services using the sources/vectors chosen at step 2 and taking in account their affordability.

To optimise the use of materials and systems as well as the construction process, we recommend promoting the use of Building Information Modelling (BIM) to improve quality and reduce energy use, emissions and costs along the lifetime of the buildings. More globally, the development of a circular economy by embracing a cradle-to-grave or cradle-to-cradle lifecycle assessment in the buildings sector will be needed.

### 7.3. **Well-balanced existing retrofit solutions to significantly reduce emissions and energy use at the lowest possible cost**

For retrofitting, we recommend that public policies facilitate obtaining the right local balance between improving the building envelope (insulation), introducing local generation (especially PV on the roof) and storage, and changing the equipment for low-carbon equipment (e.g. replacing a gas heater by a heat pump): the amount of yearly CO<sub>2</sub> reduction depends on this balance and so do the capital and operational expenses (CAPEX and OPEX) and comfort for the inhabitant.

### 7.4. **Electrification for decarbonisation, improved integration of renewables and flexibility**

Beside the specific use of electricity for information and communications technology, we recommend electrification and making electrification available for all basic uses, including:

- cooking: using electric cooking appliances (induction) if possible, and advanced cookstoves as soon as possible where biomass is still used due to the unavailability of electricity;
- lighting: using LED and lighting management systems using LED;
- water heating: using electric water heaters, heat pump water heaters;
- heating/cooling (decentralised space heating/cooling): using heat pumps, if possible, reversible if needed, and radiative heating if heat pumps are not relevant.

The increasing electrification of buildings allows their energy consumption to increase (flexibility, load shifting, peak shaving) and furthermore contributes to the high integration of remote intermittent renewables like PV and wind.

Furthermore, instead of being only energy consumers, buildings could play a greater role in the context of energy system decarbonisation through: (a) the utilisation of their roofs (and façade spaces) to install on-site renewable energy generation units, especially in low-density and low-rise buildings; (b) the integration of thermal or power storage technology in the buildings (see 7.7); and (c) the use of flexible energy to achieve demand-side management or response.

### 7.5. **District heating and district cooling in selected locations: assets in abating emissions from buildings and cities**

We recommend considering district heating networks as an asset for decarbonisation if the energy they provide, in kWh, is 'low-carbon', which may be possible for example if solar, geothermal and biomass, waste heat from industrial sites and power plants, urban waste and heat pumps are used.

In selected locations, district cooling may also be an asset if the kWh they are providing is 'low-carbon' which may be possible using the water of a lake or of the sea, as well as renewables like solar and shallow geothermal energy as well as heat pumps.

Both could benefit far more than is usually the case from inter-seasonal heat storage.

### 7.6. **Hydrogen: a limited but useful potential for buildings and cities**

Under specific conditions, hydrogen may be used to store energy from solar and wind energy. For instance, in isolated communities.

We recommend using low-carbon H<sub>2</sub>, as it may be useful to replace diesel as fuel for some non-connectable equipment needed during construction phase. We recommend fuel-cells powered by low-carbon hydrogen replacing diesel generators in case of power failure in hospitals or data centres for example.

### 7.7. **Considering buildings as energy systems to facilitate flexibility and sustainability and enhance digitalisation**

We recommend operating buildings as flexible energy systems that may be optimised to contribute to reducing emissions and energy bills through demand-side response for example - even more so if they are connected to the energy district management system, if existing.

There is a need to install sensors and to connect all principal equipment to a Building Energy Management system (BEM), which is easier for new buildings than for old ones.

Users will be made more responsible through creative business models and through better information on the operation of energy-consuming devices via appropriate interfaces, even if, in most cases, they consider it to be uninteresting.

#### 7.8. **Smart Cities to bring together smart buildings**

The smart city concept has emerged as a game changer in the building sector and supports the decarbonisation of the sector. This is equally applicable to existing buildings in developed countries, and to the stocks to be built in developing countries.

We recommend this approach, which is non-invasive and does not interfere with any of the existing technologies or processes but improves their efficiency by integrating digital technologies for optimising the use of natural resources by the town planning and operation, thus allowing carbon emissions in cities to be reduced. It is basically a systemic change with very little addition to building cost.

#### 7.9. **Renewed education and training of ‘smart enterprising builders, architects and operators’ and better information for the public**

Beyond the general awareness of sustainable technologies and their implementation on all levels of education (school, apprenticeship, engineering education, lifelong learning), we recommend paying a special attention to the needs of the building sector and thus form numerous well-trained craftspeople, from apprenticeship to continuous professional development, in the workplace. They are indeed at the root of the massive implementation of low-carbon technologies, such as heat-pumps, PV panels, BEMs and their networks, new technologies like 3D printing, etc.

Education and information of the public are needed to help the user to behave in such a suitable manner as to promote the decarbonisation and rational use of energy. Moreover, the understanding by citizens as a whole of the justifications of the regulations described above (7.1), their ‘why, how, when’, is key for such a transformation.

#### 7.10. **Social measures to ensure energy transformation policies are effective**

Decent living standards, sufficient building space and service levels are essential measures, and should be enhanced because:

- suitable building per capita floor area, low carbon building material and construction methods are key to reducing buildings embodied energy and emissions;
- passive buildings design, suitable indoor temperature, green lifestyle and ‘part time and part space’ behaviour, and natural ventilation play a crucial role in reducing building operation energy and emissions.

Solutions should concern all human beings, especially those now in situations of energy poverty and, more generally, poverty, which affects many countries and suburban areas. Such issues should thus be addressed to simultaneously improve life and reduce emissions. We recommend that every ‘green plan’ take these considerations into account.

Furthermore, policies should also be implemented and adapted to remote locations.

## List of abbreviations and acronyms

---

<b>AC</b>	Air Conditioning
<b>AC</b>	Alternative Current
<b>AI</b>	Artificial Intelligence
<b>BAPV</b>	Building Attached PV
<b>BECU</b>	Building Electricity Consumption from Utilities
<b>BIPV</b>	Building Integrated PV
<b>CCS</b>	Carbon Capture and Storage
<b>CDD</b>	Cooling Degree Day
<b>CHP</b>	Combined Heat and Power
<b>COP</b>	Coefficient of Performance
<b>DC</b>	Direct Current (Continuous)
<b>DEC</b>	Direct Evaporative Cooling
<b>EdF</b>	Electricité de France
<b>EJ</b>	ExaJoule
<b>EPC</b>	Energy Performance Certificate
<b>ESCO</b>	Energy Service Company
<b>GABC</b>	Global Alliance of Buildings and Construction, Global ABC
<b>GHG</b>	Green House Gas
<b>HVAC</b>	Heating Ventilation Air Conditioning
<b>IEC</b>	Indirect Evaporative Cooling
<b>IoT</b>	Internet of Things
<b>IPCC</b>	International Panel on Climate Change
<b>IT</b>	Information Technology
<b>LAC</b>	Latin America and Caribbean (Countries)
<b>LCA</b>	Life Cycle Assessment
<b>LED</b>	Light Emitting Diode
<b>LEEN</b>	Learning Energy Efficiency Network
<b>LPG</b>	Liquefied Petroleum Gas
<b>M&amp;V</b>	Measurement and Verification
<b>MEPS</b>	Minimum Energy Performances Standard
<b>NBS</b>	Nature Based Solution
<b>NDC</b>	National Determined Contribution
<b>NPV</b>	Net Present Value
<b>O&amp;M</b>	Operation and Maintenance
<b>PEDF</b>	Photovoltaic Energy Storage, DC current and Flexibility (Buildings)
<b>PEDF</b>	Photovoltaic Energy storage, Direct Current, Flexibility (Buildings)
<b>PLC</b>	Power Line Current
<b>PV</b>	Photovoltaic
<b>RESCO</b>	Renewable Energy Service Company
<b>RTS</b>	Rooftop Solar PV
<b>SCI</b>	Smart City Index
<b>SDG</b>	Sustainable Development Goal
<b>SDHW</b>	Solar Domestic Hotwater System
<b>SPV</b>	Solar PhotoVoltaic
<b>VRF</b>	Variable Refrigerant Flow

---

## CHAPTER 3. OIL AND GAS INDUSTRY

### Members of the Working Group

**Avidan Amos**, United States of America (Co-chair)

**Bravo Lopez Manuel**, Spain

**Carnicer Roberto S**, Argentina

**Fritz de la Orta Erwin**, Mexico

**Hernandez-Garcia Gustavo**, Mexico

**Igwe Godwin J**, Nigeria / United States of America (Co-chair)

**Meisen Axel**, Canada

**Olivier-Bourbigou Hélène**, France

**Tanguy Philippe A**, Canada / France

**Wright Dave**, South Africa

## Table of Contents

---

<b>Executive Summary</b> .....	128
<b>1. Introduction</b> .....	129
<b>2. Proposed pathways for reducing GHG emissions in the oil and gas industry</b> .....	135
2.1. CO <sub>2</sub> emissions .....	135
<b>3. The future of the petroleum industry</b> .....	142
3.1. Drivers of change and their consequences .....	142
3.1.1. Technologies .....	145
3.1.2. Products .....	146
<b>4. Interactions between society, funding and human resources</b> .....	146
4.1. Sustainable Development Goals (SDGs) .....	148
4.2. Workforce .....	149
4.3. Health .....	149
4.4. Mobility .....	149
4.5. Adaptation and resilience .....	150
<b>5. Key Messages and Recommendations</b> .....	150
5.1. Strong emphasis on reducing methane flaring and fugitive methane emissions in all phases of oil and gas production, transport, and refining / processing .....	151
5.2. Exploring additional steps to lower CO <sub>2</sub> emissions .....	151
5.3. Greater emphasis on using and improving Life Cycle Assessment (LCA) models .....	151
5.4. Continued evaluation and development of the potential of CCUS opportunities for oil and gas operations .....	151
5.5. Increased investments in R&D and training .....	151
<b>List of abbreviations and acronyms</b> .....	152

## Executive Summary

We live in the midst of the fossil energy age. Fossil energy sources provide more than 84% of global primary energy consumption (PEC), and oil and natural gas account for more than 57%. Moreover, the global use of oil and gas is increasing, especially in less developed countries: there has been an astounding threefold upsurge in worldwide PEC over the last 50 years. In 1970, total PEC was 52 500 TWh, while today's global energy demand is now over 166 667 TWh and is projected to grow to nearly 250 000 TWh by 2050. The rising use of fossil fuels is responsible for the main share of increasing anthropogenic greenhouse gas (GHG) emissions. While there is growing political, social and financial pressure – including on oil and gas companies to participate in the urgently needed transition towards stated 'net-zero' GHG emission goals - the world is not making any significant progress as emissions continue to increase for all GHGs. In 2019, the global emissions of CO<sub>2</sub> from all fossil fuel combustion amounted to 33.5 Gt, the highest level ever, with 8% (2.65 GtCO<sub>2</sub>) arising from the production, treatment, refining and transport of oil and gas. Methane is the second largest anthropogenic contributor to global climate change after CO<sub>2</sub> and is a more potent GHG (by a factor of about 30) with a shorter impact time frame. The International Energy Agency (IEA) estimated that oil and gas methane emissions were about 82.5 million tonnes in 2021 equivalent to around 2.5 GtCO<sub>2</sub>.

The energy transition needed to lower carbon intensity is complex, risky and uncertain<sup>1</sup>. The IEA projections for global energy consumption builds on three scenarios: **STEPS** (Stated Policies Scenario), which corresponds to the current situation with a continued growth trend in oil and gas production through 2050; **APS** (Announced Pledges Scenario), which corresponds to what countries have pledged under the international Paris Agreement but are by and large failing to accomplish; and the more aspirational **NZE** scenario (Net Zero Emissions by 2050). While the pace of decarbonisation remains highly uncertain, the oil and gas industry will keep adapting to the demand for lower GHG production methods and products. Our key observations and recommendations for the industry are the following.

1. Reducing methane emissions and flaring in oil and gas production are the most pressing and perhaps the most achievable and cost-effective actions to undertake for oil and gas producing countries and companies.
2. We recommend further improvements in the efficiency of oil and gas operations, including the increased use of new digital technologies and increased use of electrification of process equipment where feasible and where the electric grid has a high proportion of low-carbon energy sources.
3. Greater use of Life Cycle Assessment (LCA) models and improvements in such models are needed to determine whether actions intended to reduce GHG emissions are effective, or whether they are nothing else than 'greenwashing'.
4. Carbon Capture Utilisation and Storage (CCUS) is receiving considerable attention and investment in demonstration projects. However, the scale of viable and safe deployment, and its actual subsequent impact remain to be seen as far as applicability to oil and gas production is concerned.
5. Significant investments are needed in petroleum-focused R&D, sustainability and global equity, and especially for people and societies to chart possible paths for lowering GHG emissions from the oil and gas industry.

<sup>1</sup> <https://vaclavsmil.com/2022/03/07/how-the-world-really-works/>

## 1. Introduction

As explained in *Chapter 0*, the goal of the 2022 CAETS Energy Committee Report is to be useful to public authorities, all stakeholders in the energy sectors in our respective countries, and our national Engineering and Science Academies. The focus of this chapter on crude oil and natural gas (referred to as ‘oil and gas’) is to explore and assess the potential feasibility of lower carbon emission routes and alternatives for the production of current oil and gas products used in the transport and other sectors, the petrochemical industry and other applications. We are not focused on the myriad of end uses of these products. Oil and gas are the major drivers and components of most segments of human activity, encompassing transport, food production, steel making, concrete production, petrochemicals and the manufacture of chemicals, etc. In this report, we focus only on the supply side of petroleum and natural gas, from its extraction out of reservoirs to refinery and gas operations. Our report does not duplicate the many existing reports on petroleum, its products and their impact on climate change. Our interpretations, findings and recommendations constitute the consensus of our team members. They do not necessarily agree with the cited references nor represent the views of our respective institutions.

Fossil fuels have been known and used since antiquity. However, large-scale production, in particular of oil and gas, only started in the mid-19<sup>th</sup> century, and it has been increasing worldwide ever since. Fossil fuels now provide more than 84% of global primary energy consumption (PEC), with oil and gas accounting for more than 57% (Fig. 3.1.).

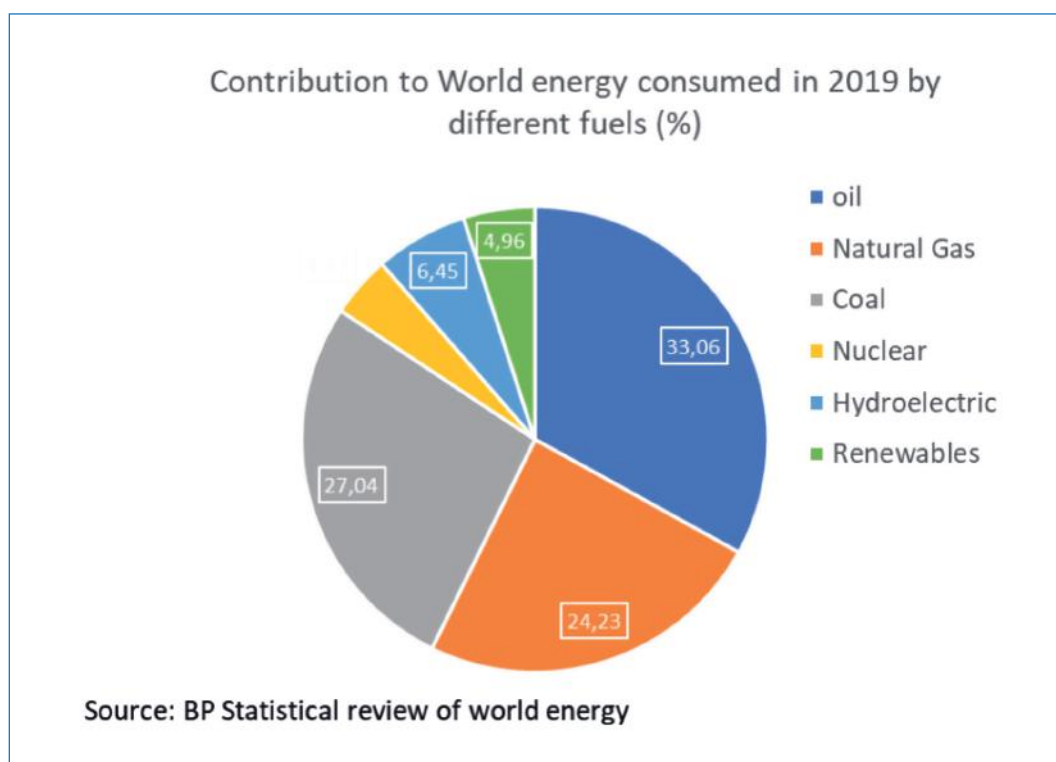


Fig. 3.1. Contribution to global PEC by different energy sources<sup>2</sup>

Global PEC fell by 4.5% in 2020 compared with 2019 due to the impact of the COVID-19 pandemic. In 2020, total PEC was 154 444 TWh, of which oil (27%) and gas (25%) represented 52%. A fast recovery was experienced in 2021 demand, reaching the level of 2019 consumption.

<sup>2</sup> BP Statistical review of World Energy, 2021 <https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html>

Global PEC was 52 500 TWh in 1970, of which oil (47%) and gas (17%) represented 64% of PEC. The increasing use of nuclear energy and, more recently, low-carbon energy sources have reduced the oil and gas percentages of PEC since the 1970s, but the percentage of coal consumption remained steady, at an average of 28% of PEC (see Fig. 3.2.)<sup>3</sup>.

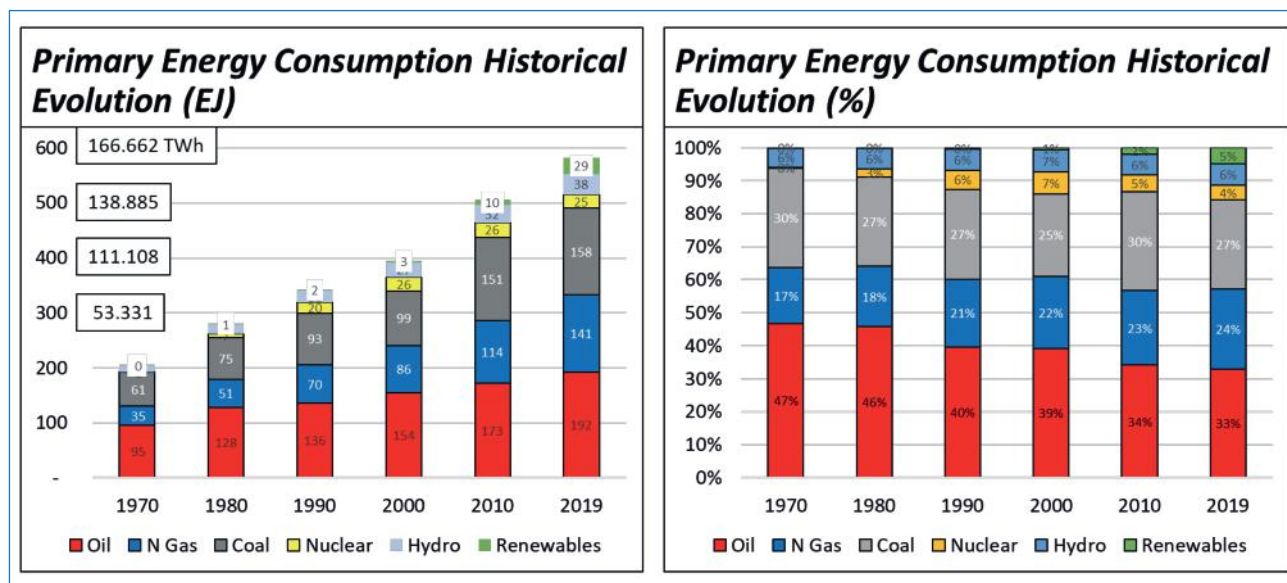


Fig. 3.2. Primary Energy Consumption (PEC)

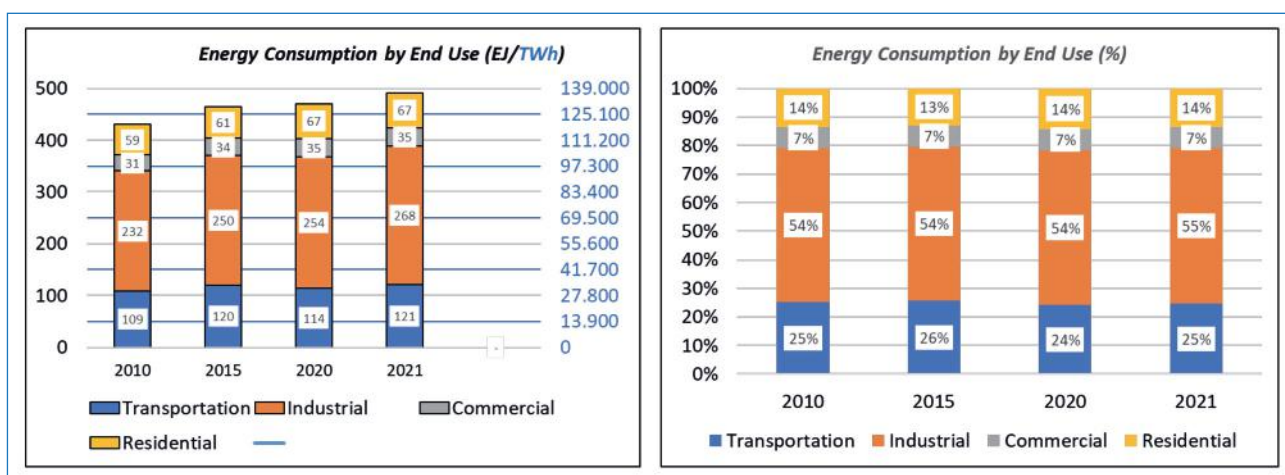
The demand growth rate for each primary energy source was different in each decade. Reasons include new technologies, price and demand changes and changes in GDP growth. Gas usage grew much faster than oil throughout this period, and it is projected to keep growing and reach a peak much later than oil. Many consider natural gas as a ‘transition fuel’, with lower GHG emissions than other fossil fuels. It has a key role in supporting low-carbon energy sources, which typically face intermittency and storage challenges. One particularly fast-growing segment of natural gas has been liquefied natural gas (LNG). LNG has two major roles – the major one being in the transport of natural gas over long distances where pipelines are not feasible. The global LNG trade increased since its inception in the early 1970s to more than 370 million tonnes in 2020, i.e. about 12% of natural gas produced. The end-use of most LNG is power generation. LNG has also been used to a lesser extent as a transport fuel, particularly for large vehicles such as ships, bus fleets and trucks.

#### *The impact of hydrocarbons on energy end use in the last decade*

Fig. 3.3.a, b, c, d, e, f, g, h below were calculated from 2021 International Energy Outlook data. They depict energy consumption by end use in several economic sectors, and by fuel. It is important to point out that the EIA definition of ‘industrial’ includes energy intensive manufacturing, non-energy intensive manufacturing and non-manufacturing.

Energy demand by end use sectors is: industrial (54%), transport (25%), residential (14%) and commercial (7%) (cf. Fig. 3.3.b.).

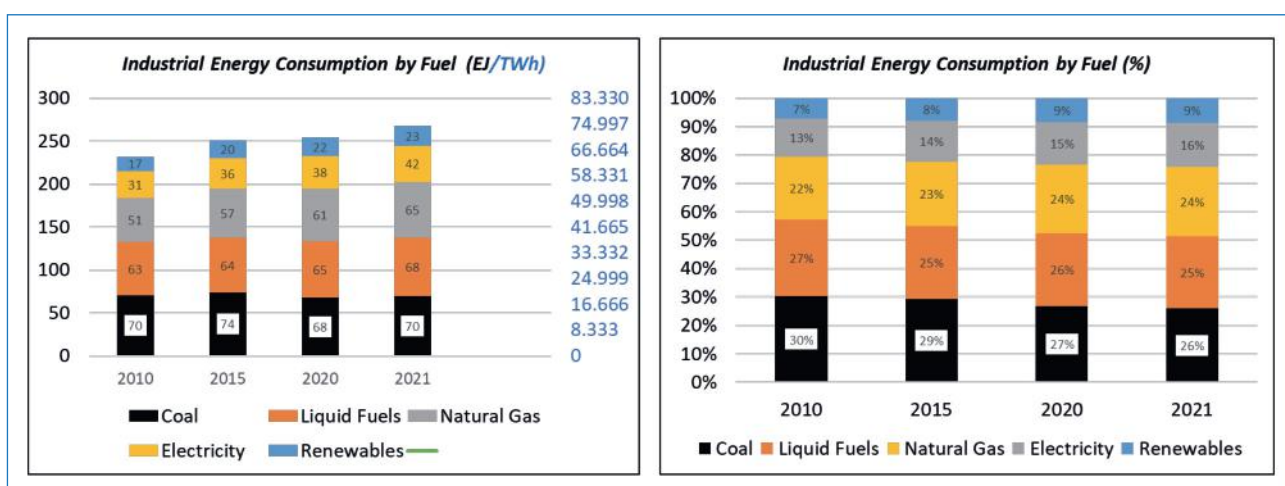
<sup>3</sup> U.S. Energy Information Administration-EIA - EIA 2021 International Energy Outlook <https://www.eia.gov/outlooks/ieo/>



(a)

(b)

Fig. 3.3.a. and 3.3.b. Energy consumption by end use

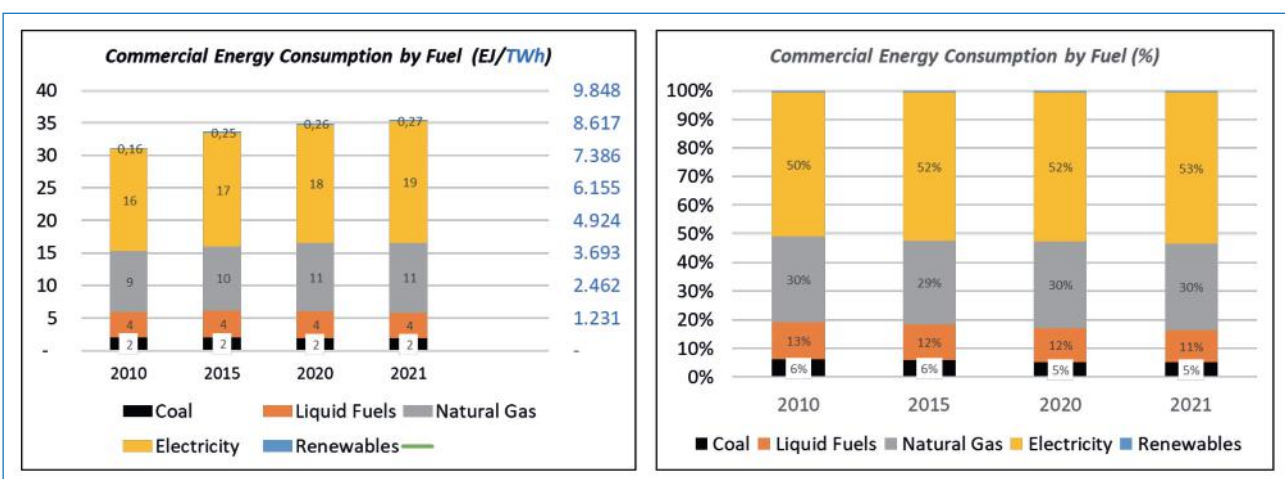


(c)

(d)

Fig. 3.3.c. and 3.3.d. Industrial energy consumption by fuel

In 2021, coal (26%), oil (25%) and natural gas (24%) represented 75% of industrial demand for a total of 268 EJ. Worldwide 61% of disposable fossil fuels are used for electricity generation. Percentage-wise, the share of natural gas in electricity generation is growing, while oil and coal are declining.

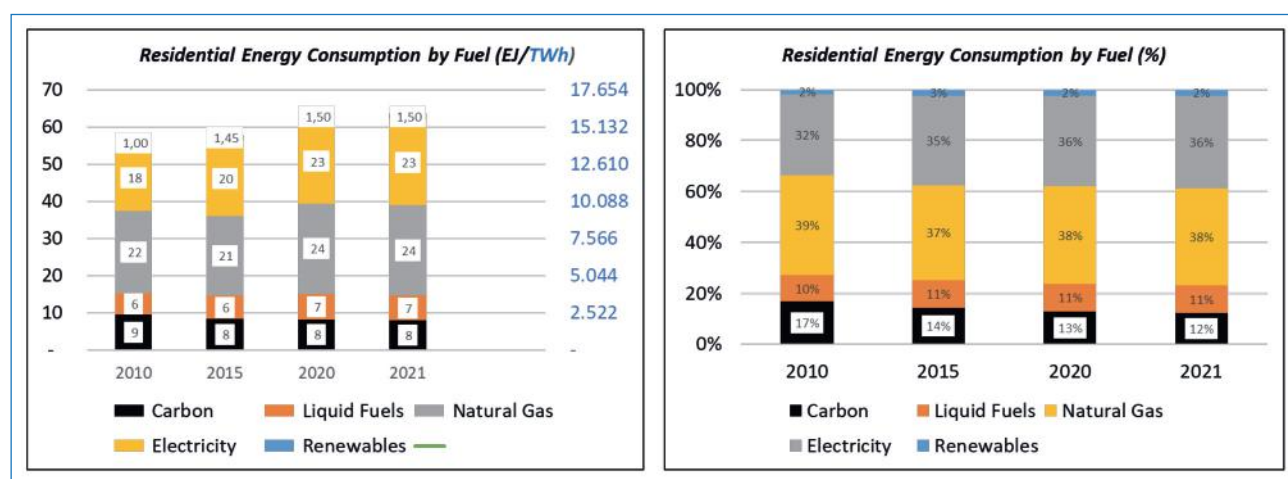


(e)

(f)

Fig. 3.3.e and 3.3.f. Commercial energy consumption by fuel

In 2021, coal (5%), oil (11%) and natural gas (30%) represent 46% of commercial demand for a total (including electricity) of 35 EJ.



(g)

(h)

Fig. 3.3.g. and 3.3.h. Residential energy consumption by fuel

Source of data for histograms in Fig. 3 a, b, c, d, e, f, g, h: EIA U.S. Energy Information Administration - International Energy outlook 2021

<https://www.eia.gov/outlooks/ieo/>

In 2021, coal (12%), oil (11%) and natural gas (38%) represented 61% of residential demand for a total of 64 EJ (17 800 TWh) (Fig. 3.3.g. and h.). Finally, energy consumption in the transport sector used 95% of oil-derived products, with a total energy consumption of 121 EJ (33 600 TWh) (Fig. 3.3.a.).

Global crude oil consumption has stabilised, or slowed down, in the developed world, but it is still increasing in developing countries, which resulted in a net increase of 1.4% annually from 2010 to 2019. It showed a rapid rebound in 2021 after a drop in 2020 due to the COVID-19 pandemic<sup>4</sup>. Its global consumption though is projected to peak sometime around 2030 or later, depending on supply and demand considerations and how fast world decarbonisation proceeds. Natural gas production and consumption have been growing faster than oil and its products and are projected to peak much later than oil.

The IEA projections for global energy consumption consider three scenarios (Fig. 3.4.)<sup>5</sup>, described below.

- **STEPS** (Stated Policies Scenario) corresponds to what is actually taking place in all the countries surveyed;
- **APS** (Announced Pledges Scenario) corresponds to what various countries have pledged under the international COP 21 Paris Agreement; and
- **NZE** (Net Zero Emissions scenario), the aspirational scenario for 2050. In IEA's World Energy Outlook 2021, the base case shows continued global increase in fossil fuels in spite of much faster growth in low-carbon energy sources through the next few decades.

<sup>4</sup> IEA, Global Energy Review: CO<sub>2</sub> Emissions in 2021. <https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2>

<sup>5</sup> IEA, World Energy Outlook 2021

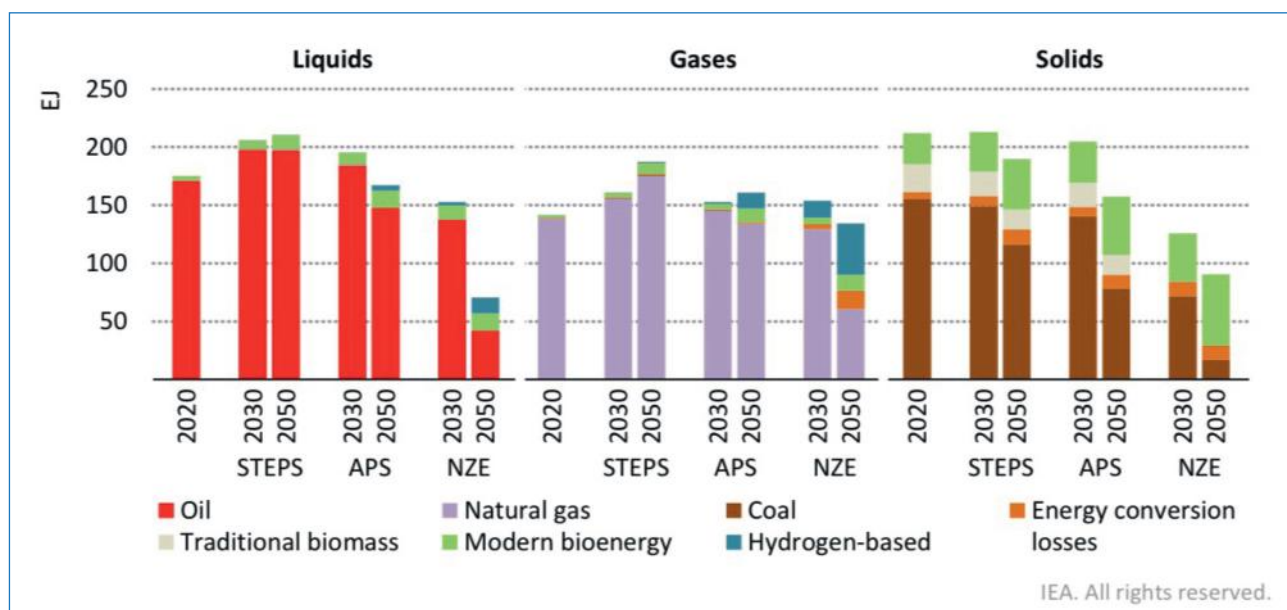


Fig. 3.4. Consumption of liquid, gaseous and solid fuels by scenario, IEA World Energy Outlook 2021 projections, p.213. Oil products consumption increases through 2050 in STEPS, and natural gas beyond 2050.

<https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf>

It is not difficult to see why it is so hard for the world to move away from fossil fuels, especially liquid and gaseous fuels [<https://vaclavsmil.com/2022/03/07/how-the-world-really-works/>]. While the rate of global population increase is slowing, UN projections show that the global population is likely to increase from nearly 8 to about 11 billion people sometime in the second half of the 21st century. By comparison, world population was estimated to be lower than 1 billion people before the start of the industrial age, and lower than 2 billion before the widespread use of fossil fuels. Increased food production and other similarly impactful technological advances have resulted in today's human population numbers, once thought to be impossible to attain and sustain. In addition to the use of petroleum products for transport, there are many other drivers for their growth. Examples include increases in polymer consumption (from 4 kg/capita in the developing world to about 60 kg/capita in the developed world) and the production of HVC (High-Value Chemicals) and methanol, ammonia and other basic chemicals<sup>6</sup>.

More important than the number of people is the aspiration of an increasing part of the global population, especially in the industrialised countries, now using much less of the world per capita GDP and energy to achieve higher standards of living and a better quality of life. Another major trend that can contribute to increasing energy demand is the projected continued urbanisation, leading to the doubling of the number of people living in large cities, with perhaps as many as 70% of the world population in the second half of the 21<sup>st</sup> century living in or around large megacities, according to the UN Department of Economic and Social Affairs projections. Hence, global PEC is projected to keep increasing significantly, and while low-carbon energy use is growing faster, much of the new increase in global demand could still be supplied by fossil fuels for a long time to come.

All major energy transitions in the past have been relatively gradual, with overlapping shares of energy sources. As far as fossil fuels are concerned, the transition has been mostly additive, rather than a replacement. For example, oil and gas did not completely 'replace' coal – today's global use of coal is the highest it has ever been. Similarly, the use of low-carbon energy sources has been additive, though it can be argued that if it were not for low-carbon energy sources, more fossil fuels would have been used. As described long ago by the Jevons Paradox, or what is usually termed today as the 'Rebound Effect', improvements in efficiency and new sources of energy lower their cost and can contribute to increasing the use of energy.

<sup>6</sup> IEA, The Future of Petrochemicals (2018). [https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The\\_Future\\_of\\_Petrochemicals.pdf](https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The_Future_of_Petrochemicals.pdf)

Considering the importance and the prominent role of fossil fuels in all aspects of civilisation, the transition from fossil fuels is likely to take decades as well, with a pace determined by commitment and feasibility, technology breakthroughs, the availability of massive global investments, and other global factors. Moreover, the transition cannot be driven on the **supply side** only. **The demand side** is equally important, but political actions impacting demand, such as higher taxation, setting a high price for CO<sub>2</sub>, emission trading systems, etc. are far more complex to design, more difficult to implement, and entail slower responses, since the outcome depends on personal decisions, social conditions in each country and the flexibility of changing use patterns. To date, little is being done to address the demand side in many countries.

The base case (according to the IEA), even assuming that governments will somehow deliver on their climate promises (which has not been the case so far), still shows the share of fossil fuels to be probably over 70% through 2040. Many published scenarios roll out the possible ranges and paces of such a transition, from the overly pessimistic to the overly speculative, aspirational, or even misleading ones. Transparent data and clearly stated assumptions are essential for evaluating scenarios. They allow the underlying facts to be checked, physical laws and constraints to be complied with, and the uncertainties and long-term consequences to be understood.

This is where Life Cycle Assessment (LCA) models are critical (See Annex 1.3. of Chapter 0: “To set the Scene”). Attributional LCA models are typically used by regulators, and they can be comprehensive, such as ‘well-to-wheels’ models, but they do not always capture all the rebound effects, unknowns, uncertainties, or unintended consequences. Consequential LCA models are increasingly employed to add some of these indirect and follow-up effects but their long-term prediction accuracy and completeness remain to be proven. LCAs are useful, yet they mostly address the supply side of liquid fuels (biofuels, gasoline, diesel, natural gas, etc.). The IPCC uses *Integrated Assessment Models*, or IAMs, or versions of LCA termed Societal-LCA, or S-LCA, which focus on the demand side, on the impacts on societies, economies and climate change, and hence indicate what real sustained reductions in energy use and GHG emissions may be achieved.

There are many examples of LCAs and IAMs being used to evaluate the carbon footprint of oil and natural gas production and delivery systems. One example for a specific LNG supply chain is provided by Roman-White et al<sup>7</sup>. The authors examined a specific project and route of liquefying US natural gas in Cheniere’s Sabine Pass LNG facility and sending such LNG to China, where it is regasified and used in power generation, hypothetically replacing coal. The LCA system boundary encompasses natural gas production (and resulting methane emissions), gas treating and transport via pipeline to the LNG liquefaction plant, then liquefaction and storage, loading and transport via LNG ships, and finally receiving, regasification and power generation in China. An overall reduction in GHG intensity of approximately 50% is calculated vs. a coal power generation LCA. The study also accounts for methane emissions throughout the whole chain. Using the standard twenty-year time horizon, methane emissions contribute more than 77% of GHG emissions in gas production, about 40% in gas processing, 58% in the transmission of gas to the LNG plant, and 43% in shipping and regasification.

Another recent example is the use of LCA to estimate the potential of GHG emission reduction from the production of shale oil and gas in the Permian basin – a major source of increased US oil and gas production, and methane and CO<sub>2</sub> emissions<sup>8</sup>. The authors considered options for reducing GHG emissions related to Permian basin operations. They found that CO<sub>2</sub> could be reinjected into conventional oil formations to enhance oil recovery and then sequestered into saline aquifers or unconventional gas formations in the form of CO<sub>2</sub>-based fracturing fluids. The authors concluded that much but not all of the Permian basin natural gas can be partially “decarbonised” if the CO<sub>2</sub> is sequestered in these ways.

<sup>7</sup> S. A. Roman-White et al: LNG Supply Chains: A Supplier-Specific Life-Cycle Assessment for Improved Emission Accounting; ACS Sustainable Chem. Eng. 2021, 9, 10857-  
<https://pubs.acs.org/doi/pdf/10.1021/acssuschemeng.1c03307>

<sup>8</sup> U. Singh, J.B. Dunn: Shale Gas Decarbonisation in Permian Basin is it Possible. ACS Eng. Au 2022, 2 3 248-256.  
<https://pubs.acs.org/doi/10.1021/acseengineeringau.2c00001>

Another example is the aviation sector. Despite improvements in aircraft efficiency, the impact of this sector on climate change is a growing concern. The International Civil Aviation Organization (ICAO) established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to help reduce aviation greenhouse gas (GHG) emissions [<https://doi.org/10.1016/j.rser.2021.111398>]. Four elements proved key to the agreed LCA method: (1) the use of life-cycle accounting for GHG emissions; (2) the inclusion of indirect land use change (ILUC); (3) safeguards to prevent deforestation; and (4) the crediting of practices that mitigate the risk of land use change (LUC). The CORSIA LCA method constitutes a good first step, but it is not perfect yet. Most credits in the CORSIA scheme come from carbon credits, which can be controversial as the amount of so-called ‘sustainable aviation fuel’ (a blend of biofuel with conventional jet fuel) is a fraction of one per cent at present. There are many critics of CORSIA and the real outcome (reducing GHG emissions from aviation) remains to be seen.

## 2. Proposed pathways for reducing GHG emissions in the oil and gas industry

Global fossil fuel combustion-related CO<sub>2</sub> emissions reached 33.5 GtCO<sub>2</sub> in 2021, about 0.22% higher than 2019 (IEA Global Energy Review)<sup>3</sup>. They accounted for about 67% of overall world greenhouse gas (GHG) emissions. Although CO<sub>2</sub> emissions are the largest GHG source in the energy sector, methane emissions are the second largest and constitute an important cause of global warming. In addition to natural sources of methane and fugitive methane emissions from the production of coal, oil and natural gas, other significant major sources of methane emissions are agriculture, land clearing, and animal husbandry. Other GHG emissions, not addressed in our chapter, although at much lower amounts, include nitrous oxide, HFCs, and others.

### 2.1. CO<sub>2</sub> emissions

In 2021 the total global annual emissions of CO<sub>2</sub> from fuel combustion amounted to 33.5 GtCO<sub>2</sub><sup>(4)</sup>, with 8% (2.65 GtCO<sub>2</sub>) arising from the production, treatment, refining and transport of oil and gas. In addition, more than 0.0825 Gt of methane, another greenhouse gas, equivalent to 2.5 additional Gt of CO<sub>2</sub>-e, was emitted<sup>9</sup>. These emissions (estimated to be 5.1 GtCO<sub>2e</sub> in 2021) account for as much as 12.5% of the world overall energy-related GHG emissions (40.8 Gt CO<sub>2e</sub>) and 24% of those corresponding to oil and gas fuels.

Minimising greenhouse gas emissions from oil and gas operations (production, treatment, refining and transport) is a critical priority. This can be done via the improvement of energy efficiency by:

- the implementation of Energy Management Systems (EMS): an efficient EMS improves the management of energy and helps design actions to increase energy efficiency;
- digitalisation to support the EMS by the deployment of equipment and software for data acquisition, performance monitoring and AI, in particular, machine learning;
- Improving the refining of catalytic processes and heat integration inter-process units;
- Replacing fossil fuel heating with electrical heating using low-carbon energy as well as electrifying other equipment and systems where possible;
- Applying carbon capture, utilisation and storage (CCUS);
- Reinjecting gas to enhance oil recovery.

At present, these initiatives are undertaken either voluntarily by companies or in response to country policies and regulations, particularly in refining, which is the largest CO<sub>2</sub> emitter in the oil and gas production chain.

Refineries are complex installations, with process units selected for the type of crude oils to be processed and target markets for the product. Refiners have been under pressure from regulations, which forced them to increase the number of their process units and adapt their processes to the new market demands, new product specifications, and environmental regulations – thereby increasing energy consumption and CO<sub>2</sub> emissions, while at the same time significantly improving energy efficiency.

<sup>9</sup> IEA, Global Methane Tracker, Feb. 2022. <https://www.iea.org/data-and-statistics/data-product/methane-tracker-database-2022#>

- » Case studies show that the move from 'no-EMS' to the implementing of a 'full-EMS' might achieve about 10% of energy savings<sup>10</sup>.
- » Distillation has been identified as offering the largest opportunity for reduction in energy consumption; Such reduction has been suggested to reach 10 to 15% through the implementation of existing technologies, including:
  - installing pre-flash columns;
  - optimising column inlet temperatures;
  - reducing coking in furnaces and the fouling of heat exchangers;
  - maximising the distillate in the atmospheric column;
  - implementing advanced controls, such as dynamic matrix control (DMC);
  - replacing column internals with higher efficiency trays.
- » The heat integration of the process units offers the possibility to reduce bottlenecks and to improve the efficiency of heat exchange; however, increased interdependency between units must be carefully assessed, especially for start-ups and unplanned shutdowns.
- » Integration with petrochemical plants allows the feedstock and products (e.g., hydrogen) to be shared in addition to energy distribution networks (steam gas and power), with benefits in terms of economy of scale and improved optimisation.

Additionally, refineries reduce CO<sub>2</sub> emissions by:

- Increasing crude treatment flexibility and the conversion of refineries. This allows them to cope with the market changes of petroleum products. World oil consumption increased in the period 2010-2019 at a mean annual rate of 1.4%, whereas the consumption of light and medium distillates increased by 1.7% annually and heavy fuel oil decreased by 2.4%; this shows that refining conversion could allow refineries connected to a natural gas network to reduce fuel oil firing and replace it with natural gas, with a reduction of 20 to 25% in CO<sub>2</sub> emissions.
- Installing cogeneration facilities: as a significant proportion of refinery energy needs are supplied by steam, installing cogeneration within the refinery energy system is advisable (or high-efficiency CHP). In this way, refineries can produce electricity at a carbon intensity of about 350 kgCO<sub>2</sub>/MWh as a substitute for network electricity, and drive the reduction in CO<sub>2</sub> emissions when network carbon intensity is higher.

### *Methane Emissions*

In addition to venting and flaring large quantities of gas (mostly methane) in many remote oil production facilities, much methane gas is being released into the atmosphere. The International Energy Agency (IEA) estimated that worldwide oil and gas methane emissions were about 0.0825 Gt in 2021, i.e. 3.6% lower than in 2019, which is mainly due to lower production activity and actions for reduction (see Fig. 3.5.)<sup>10</sup>. As methane has a global warming potential about 30 times higher than CO<sub>2</sub> over 100 years (and 80 times for a 20-year time horizon), this amount of emitted methane is equivalent to 2.5 Gt of CO<sub>2</sub> equivalent (CO<sub>2e</sub>)<sup>11</sup>, a figure equivalent to 90% of the energy emissions of the European Union in 2020. This is also comparable to the CO<sub>2</sub> emitted for petroleum production, transport, refining and processing (i.e. 2.65 GtCO<sub>2</sub>).

<sup>10</sup> IEA: Curtailing Methane Emissions from Fossil Fuel Operations Oct. 2021. <https://www.iea.org/reports/methane-tracker-2021>

<sup>11</sup> Energy Transitions Commission: Keeping 1.5 °C Alive: Closing the Gap in the 2020s, Sept. 2021

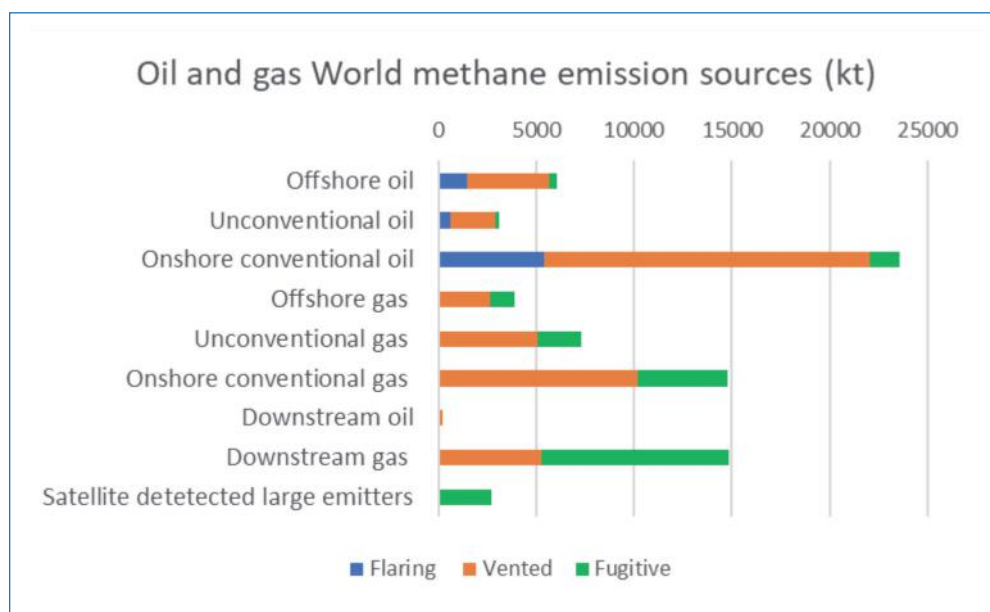


Fig. 3.5. IEA estimation of oil and gas methane emissions by source in 2020

Source of data for histogram: IEA 2021 Methane tracker.

<https://www.iea.org/reports/methane-tracker-2021>

Anthropogenic methane emissions are the second largest cause of global warming behind CO<sub>2</sub> and seem to be growing at a faster rate than CO<sub>2</sub> in the atmosphere. Oil and gas production and supply are among their largest sources (Fig. 3.6).<sup>9</sup> As a result, the most effective short-term measure to reducing GHG emissions from the oil and gas sector is to reduce methane emissions from crude oil and natural gas production-sites. Government policies are important tools in encouraging the oil and gas sector to implement reduction measures and investments in order to reduce methane emissions and progress in achieving the global climate goals.

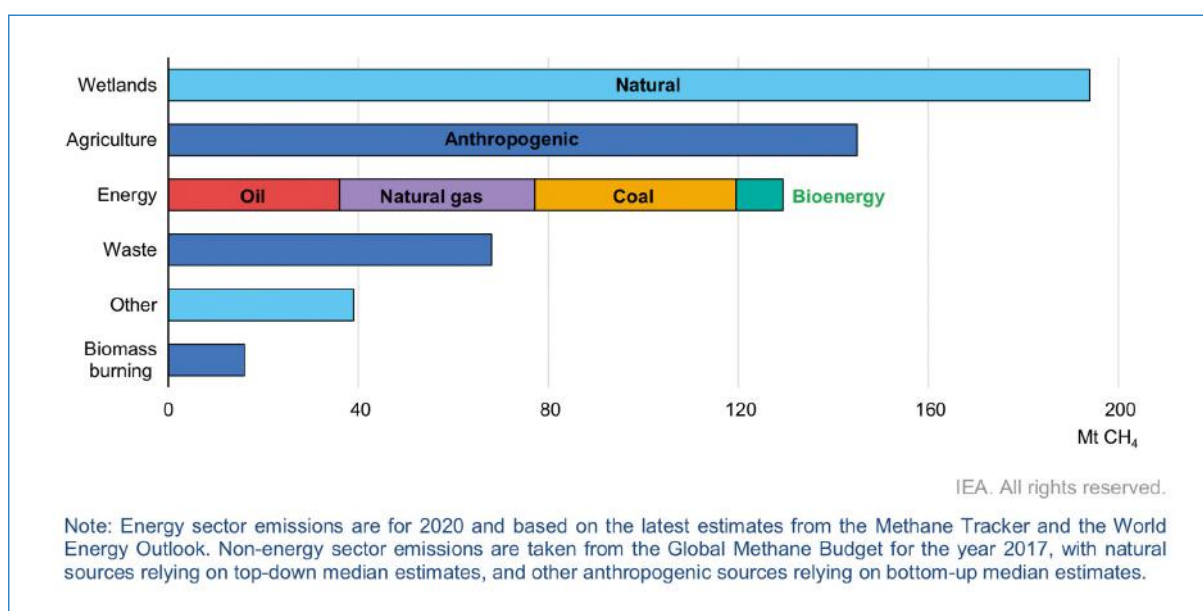


Fig. 3.6. World sources of methane emissions

IEA, "Curtailling Methane Emissions from Fossil Fuel Operations, Pathways to a 75% cut by 2030" Page 11

<https://iea.blob.core.windows.net/assets/ba5d143a-f3ab-47e6-b528-049f81eb31ae/CurtaillingMethaneEmissionsfromFossilFuelOperations.pdf>

As mentioned earlier, Fig 3.6. shows that methane emissions from oil and gas operations are one of the largest contributors to anthropogenic methane emissions. However, technologies that may abate and prevent methane emissions from oil and gas operations are available and well known.

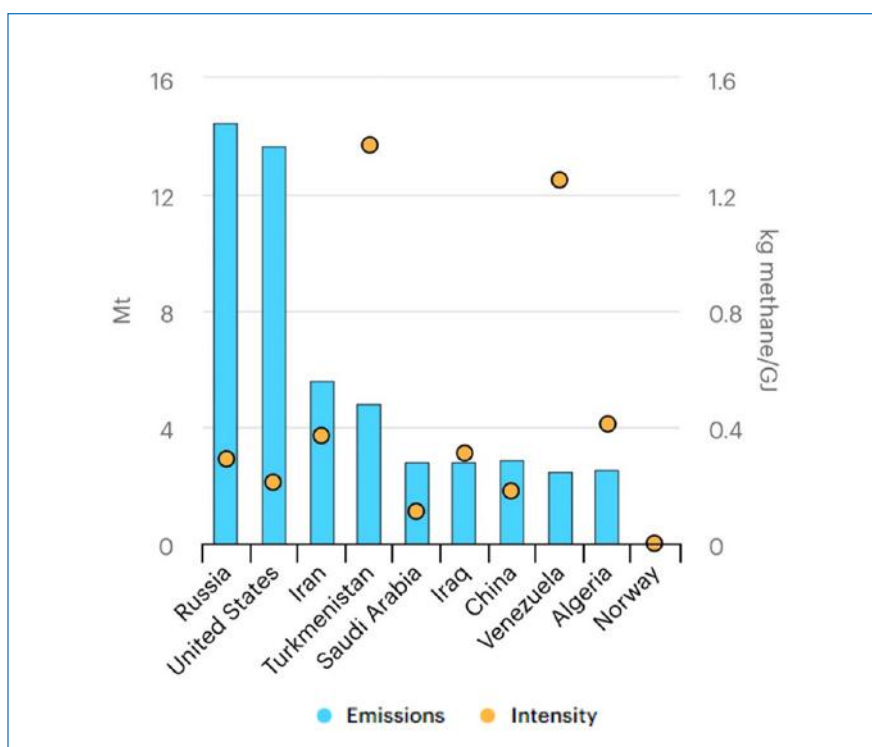


Fig. 3.7. Total methane emissions and methane intensity of production in selected oil and gas producers, 2021

Source: IEA, Methane Emissions from Oil and Gas Operations, Tracking report — September 2022, IEA. License: CC BY 4.0

<https://www.iea.org/reports/methane-emissions-from-oil-and-gas-operations>

Methane abatement offers some of the most cost-effective opportunities to reduce emissions, as, in many cases, the gas saved can allow the required investment to be quickly recovered; the IEA estimates that 45% of emissions can be abated at no net cost under 2021 gas prices<sup>9</sup>. A reduction by 60% or more by 2030 should also be possible (Energy Transitions Commission, September 2021) if the necessary incentives for investment are provided (e.g. regulations, the creation of a domestic natural gas market where none exists, pipelines, etc.).

Methane and other GHG emissions take place during venting and flaring, especially as a consequence of production upsets, equipment operation and fugitive losses. Actions to assist in the reduction of these emissions are as follows:

- Reduce continuous and unplanned emissions by the introduction of predictive maintenance, supervisory control, sensors, and advanced data analysis;
- Reduce fugitive emissions by leak detection and repair (LDAR);
- Replace pneumatic pumps and controllers and apply the best available technologies for pumps, compressors and valve seals to reduce emissions and leaks;
- Install vapour recovery units.

Many oil and gas producers have already voluntarily undertaken steps to minimise methane emissions from flaring and venting and have set voluntary emission reduction targets for the next years. As an example, some IOGP members established methane intensity targets for their upstream operations, typically 0.2% of the marketed gas volumes<sup>12</sup>.

Countries seeking to develop policies and regulations in this area should learn from the experience of regional or national administrations and companies that have already implemented methane-related guidelines and regulations in order to establish voluntary and regulatory frameworks suitable for local conditions.

Policies, however, are not effective without appropriate tools for measuring the emissions and accurately reporting them to the authorities. These actions can assist in improving regulatory effectiveness. Even though more sophisticated measurement tools are still in development, others that apply to known emission sources, in particular by the most prominent emitters, can be applied immediately, which would be useful for establishing a credible monitoring programme.

Measures used for methane emission assessment include the digitalisation of operations, ground-breaking new technologies to operate more effectively, and the detection of methane leaks by drones and satellites. The adoption and deployment of core technologies enabling the Internet of Things (IoT), which essentially integrates sensor communication and data analysis, can display great opportunities for the control of emissions.

Methane emissions can be detected and traced in some cases, but they could be hard to detect in other cases. Tractable emissions can be defined as those stemming from point sources that can be easily identified. When they are found, mitigation measures can often readily be undertaken. Super emitter leaks from production wells and pipelines are at one end of the tractable spectrum while abandoned installations are at its other end and both of these should be targeted first. Example: In the Barnett Shale gas field (fracking) in Texas, where a massive methane leak was developing (Zavala-Araiza et al. 2015)<sup>13</sup>

As the table below shows, the detection of methane fugitive emissions has made significant progress and a number of sensing technologies can be used depending on the size of the measured element.

Scale of measurement	Size of measured element	Measurement and model methods	Purpose/ use of data
Regional	100's km	Satellite, towers, airborne, ICOS, regional inverse models	Detect oil and gas methane emission hotspots, estimate regional fluxes
Sub regional	10's km	Airborne (in-situ and remote sensing)	Source detection, basin-wide estimates (e.g., mass balance techniques).
Facility	100's m to 1 km	Airborne (in-situ or remote sensing), ground based, mobile surveys, optical remote sensing, inverse dispersion models.	Identify super-emitters, facility-wide emission factors.
Site area/unit	100's m	Optical sensing techniques	Emission reporting, input to facility scale reporting, leak identification.
Component	<1m	Sniffing, optical gas imaging, Hiflow	Individual leak quantification, mitigation – leak detection and repair programs. Component scale emission factor development

**Table 3.1.** Available measurement and modelling techniques (UNECE 2019)

UNICE - Best Practice Guidance for Effective Methane Management in the Oil and Gas Sector – Monitoring, Reporting and Verification (MRV) and Mitigation, August 2019, Pages 20/21. An updated version of the report, however without the table, is available here:

[https://www.globalmethane.org/documents/Best\\_Practice\\_Guidance\\_for\\_Effective\\_Methane\\_Management\\_in\\_the\\_Oil\\_and%20Gas\\_Sector\\_2019.pdf](https://www.globalmethane.org/documents/Best_Practice_Guidance_for_Effective_Methane_Management_in_the_Oil_and%20Gas_Sector_2019.pdf)

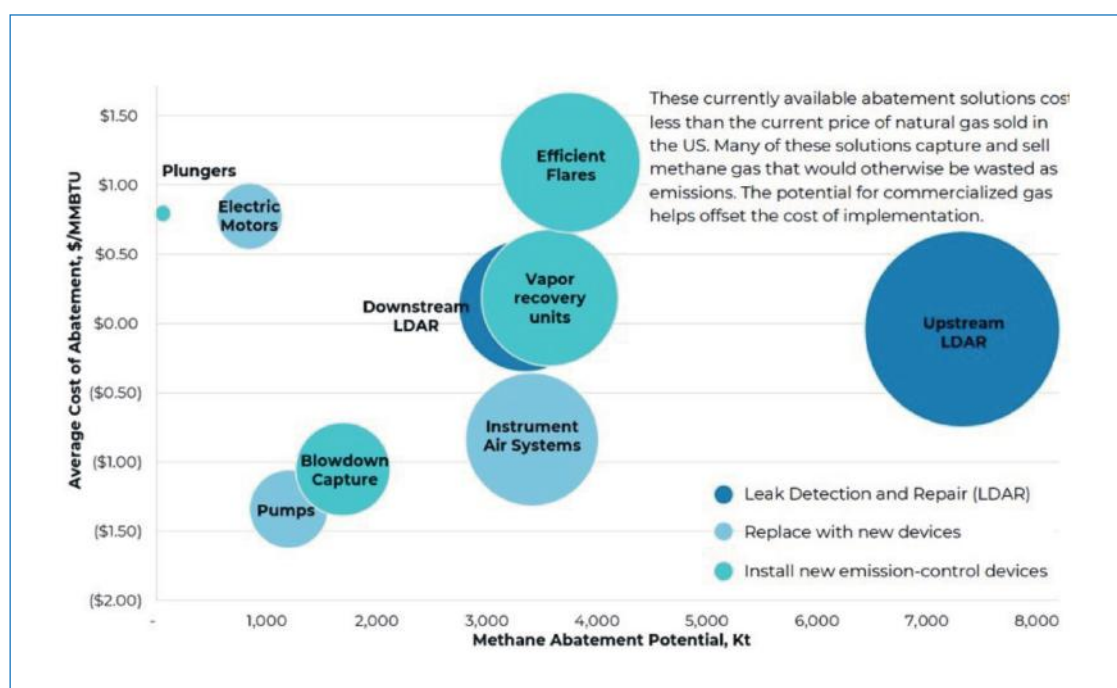
<sup>12</sup> International Association of Oil and Gas Producers; Methane Management in the Upstream Oil and Gas Industry <https://iogpeurope.org/wp-content/uploads/2020/04/Methane>

<sup>13</sup> D. Zavala-Araiza, et al. Toward a Functional Definition of Methane Super-Emitters: Application to Natural Gas Production Sites; Env. Sci. Technol. 2015, 49, 13, 8167 <https://doi.org/10.1021/acs.est.5b00133>

An innovative example of technology combination is the partnership between TotalEnergies and GHGSat. The companies developed satellite imaging technology to monitor potential methane leak occurrences at offshore facilities and combined it with local measurements using a drone-mounted spectrometer. TotalEnergies has thus been able to cut its emissions by nearly half since 2021, and the company objective is to maintain emissions intensity below 0.2% of commercial gas produced in oil and gas facilities and below 0.1% in gas facilities.

The abatement of methane emissions is not necessarily a cost as the recovered gas can be monetised. *Fig. 3.8.* below, from GEC Advisors LLC [[www.geclp.com](http://www.geclp.com)], illustrates the average cost of abatement vs. the abatement potential.

For example, the Chinese company CNPC was able to cut emissions by 12.3% in 2019 in the Dagang oilfields during a leak detection and repair (LDAR) pilot campaign. Recovering the associated natural gas from oilfields is now an integral part of the company's operations. Vent gas from remote wells that have no pipeline access is now recovered, low-pressure associated gas is pressurised into gathering pipelines, and recovered gas is used to provide drilling power to rigs and auxiliary generators. As highlighted in the OGCI website, in the Tarim oilfield, 48 gas recovery stations have been set up, with a capacity of 4.2 million cubic meters per day<sup>14</sup>.



**Fig. 3.8.** Net-zero cost solutions for abatement of methane emissions  
Kimberly L. Bell, GEC (2021)

<https://www.geclp.com/apprehending-fugitive-emissions-applying-innovative-technologies-to-capture-escaping-methane-gas/>

Across many of the world's natural gas production fields, gas pneumatic devices used for process control and chemical injection vent methane directly into the air. Qnergy (qnergy.com) has developed a solution that allows converting methane powered instrumentation to compressed air powered instrumentation, thus eliminating the release of methane to the atmosphere during the process. During a successful pilot project at the Barnett site in March 2021, Qnergy's technology enabled the elimination of up to 98% of the methane venting emissions related to instruments using natural gas. A major petroleum company operating in the Barnett field has now decided to install 400 of such units that will allow methane venting to be abated by about 7 000 tonnes/yr.

A number of publicly available reports already documented best practices to reduce methane emissions in the oil and gas value chain. The table below gives an overview of the main abatement options by emission source categories (Best Practice Guidance for Effective Methane Management in the Oil and Gas Sector Monitoring, Reporting and Verification (MRV) and Mitigation, August 2019, Torleif Haugland, UNECE).

<sup>14</sup> <https://www.ogci.com/case-study/cnpc-tackling-methane-emissions/#:~:text=Reducing%20methane%20emissions%20from%20oil,upstream%20methane%20intensity%20by%202025>

The options described in *Table 3.2.* below provide many practical ways to reduce methane emissions and should be diligently implemented as soon as possible in every operation.

Emission source	Abatement options	Methane emission reduction for the emission source
<b>1. Hydraulic fracturing &amp; well completion</b>	Green completion system	95%
<b>2. Casing head venting from oil wells</b>	Install compressors/VRU to capture casing head gas or connect casing to tanks equipped with VRUs or re-route casinghead gas to flare (note: the latter alternative increase CO2 emissions)	
<b>3. Liquids unloading from gas wells</b>	Install plunger lift systems in gas well	Variable
	Manually redirect the well to the production system as soon as the unloading is completed	Variable
	Plunger Lift optimization	Variable
	Add foaming agents, soap strings, surfactants	
<b>4. Glycol dehydrators</b>	Install velocity tubing	Up to 90%
	Install flash tank separator and optimise glycol circulation rates	
	Route flash tank (if present) and dehydrator regenerator vents to VRU for beneficial use	Up to 98%
	Route flash tank (if present) and dehydrator regenerator vents to flare (note: increase CO2 emissions)	
<b>5. Natural gas driven pneumatic controllers and pumps</b>	Replacing by zero emissions (e.g. desiccant) dehydrators	100%
	Replace the gas assist lean glycol pump with an electric lean glycol pump	Up to 95%
	Reroute glycol skimmer Gas	Up to 97%
	Replacement or retrofit to from high bleed to low bleed devices	Up to 95%
<b>6. Wet-seal centrifugal compressors</b>	Routing emissions to an existing combustion device or vapor recovery unit	Up to 90%
	Ensure intermittent bleed controller are properly functioning i.e. only vents/emits during the de-actuation portion of a control cycle with no emission when the valve is in a stationery position.	
	Replacement by zero emission options (electric or air driven)	100%
	Re-route gas at lower pressure to VRU, flare, or to a low-pressure inlet	Up to 95%
<b>7. Reciprocating rod-packing compressors</b>	Convert compressor wet seals to dry seals	Variable
	Regular replacement of rod packing (ideally based on measured emission rate)	Typically, 50-65%
	Re-route vents points to VRU or fuel gas system	Up to 95%
	Re-route vents points to flare (note: increase CO2 emissions)	Up to 95%
<b>8. Venting associated gas at upstream oil production facilities</b>	Flaring without energy recovery instead of venting <sup>88</sup>	Up to 98%
	Capturing vent gas for gas utilization	up to 100%
	Install flare ignition systems <sup>89</sup>	Variable
<b>9. Hydrocarbon liquid storage tank, loading &amp; transportation, produced water discharge<sup>90</sup></b>	Reduce operating pressure upstream <sup>91</sup>	Up to 30%
	Increase tank working pressure	10-20%
	Change geometry of the loading pipe	Poor data
	Installing a Vapor Recovery Unit (VRU) and directing to productive use as fuel gas, compressor suction, gas lift	Up to 98%
<b>10. Equipment depressurization and blowdowns from pipelines and facilities</b>	Hydrocarbon blanketing <sup>92</sup>	Variable
	Install separate systems to control loading losses from the tank vehicles and storage losses from the tanks. Implement a system to balance or exchange vapors between the tanks and tank vehicles and add a common vapor control device if needed	
	Install stabilization towers ahead of tanks to obtain a low oil vapor pressure suitable for loading onto ships or barges.	Variable
	Use Isolation valves to minimize impact	
<b>11. Component and equipment leaks</b>	Re-direct gas into storage vessel (field), flare, or low-pressure header (fuel gas or gathering system)	Variable
	Minimise the number of starts ups	
	Lower pressure in the pipeline prior to event through main line compressors and a mobile compressor stations (for pipeline repairs)	Variable
	Install plugging equipment to shorten segment of pipeline involved in outage. Use isolation valves to minimize impact	
<b>12. Incomplete combustion (including Associated petroleum gas (APG) flaring, engines, turbines, fired heaters)</b>	Rerouting the natural gas to a duct burner, thermal oxidizer or flares where possible (upstream) to recover a portion of all of the blowdown gas.	Variable
	Perform LDAR	Depends on frequency <sup>93</sup>
	Implement effective leak-prone pipe replacement program.	Variable
	Planned / carefully executed activities when excavating	
<b>12. Incomplete combustion (including Associated petroleum gas (APG) flaring, engines, turbines, fired heaters)</b>	Abandoned or suspended wells: Plug the well	Variable/poor data
	Install automated air/fuel ratio controls	
	Minimise the number of start-ups	Variable
	Installing catalytic converters on gas fuelled engines and turbine	
<b>12. Incomplete combustion (including Associated petroleum gas (APG) flaring, engines, turbines, fired heaters)</b>	Increase combustion efficiency by upgrading to more efficient engines/turbines	Variable
	Minimize gas flaring by utilising the gas	Variable
	Improve combustion efficiency by Change flare tip / installing flare ignition systems <sup>94</sup>	Increase to up 99.8% combustion efficiency

**Table 3.2.** Main abatement option by emission source UNECE: Best Practice Guidance for Effective Methane Management in the Oil and Gas Sector Monitoring, Reporting and Verification (MRV) and Mitigation August 2019, Pages 38/39.

[https://unece.org/fileadmin/DAM/energy/images/CMM/CMM\\_CE/BPG\\_Methane\\_final\\_draft\\_190912.pdf](https://unece.org/fileadmin/DAM/energy/images/CMM/CMM_CE/BPG_Methane_final_draft_190912.pdf)

### 3. The future of the petroleum industry

This section considers the potential future of the global petroleum industry in the long term, i.e., twenty or more years into the future. While details of the long-term future are inherently uncertain, cannot be accurately predicted by mathematical models, and vary by region and country, it is likely that the future global petroleum industry will differ greatly from today's industry. The reasons for change are several major drivers and their interactions, resulting in the potential emergence of two distinct but connected subindustries, both reliant on petroleum feedstocks. The emergence of the distinct subindustries may be gradual but will likely accelerate over time.

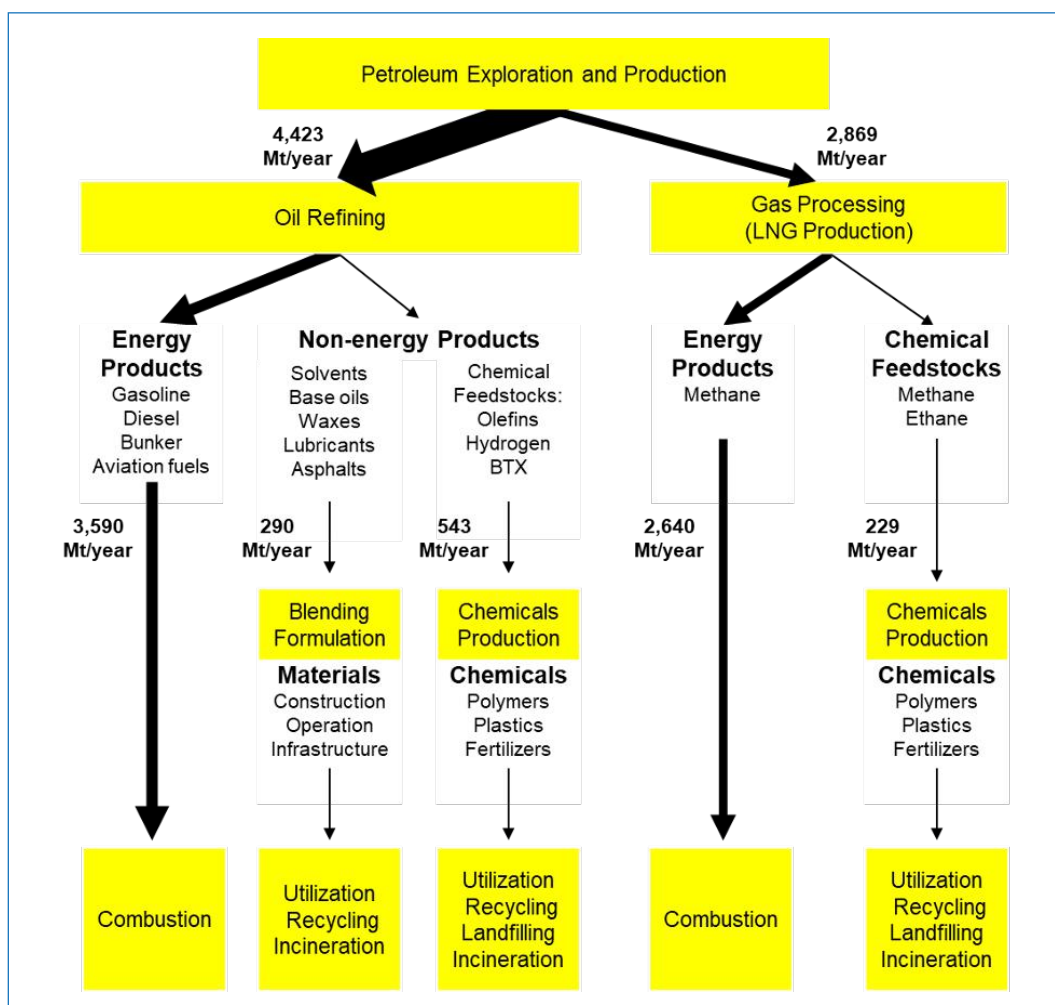
#### 3.1. Drivers of change and their consequences

The following drivers of change are expected to have an increasing impact on the global petroleum industry:

- a. Sustainability concerns and commitments related to greenhouse gas emissions, their impact on climate change, and the need to reduce such emissions.
- a. As stated elsewhere in this chapter, emissions arise during the exploration, production, transport, refining / processing of petroleum and, most importantly, the use of the industry's primary products: the combustion of fuels used in transport, heating, and heavy industry. The latter three are excluded from consideration in this chapter.
- b. Advances in energy and carbon supply from sources other than petroleum-derived products, including electricity, hydrogen, biomaterials, biofuels and waste.
- c. Electrification, especially of the transport and manufacturing sectors.
- d. The electrification of personal transport is driven by improved battery technologies and reduced vehicle manufacturing costs but tempered by the supply of electricity and possibly the availability of critical minerals.
- e. Advances in carbon capture, utilisation and storage (CCUS).
- f. Rising global populations and prosperity leading to increased demands for energy.
- g. The emergence of new energy products, including hydrogen and ammonia, on a regional and global basis
- h. Growing global demands for materials and chemicals (related to housing, infrastructure, clothing, etc.) and nutrients (mainly for plants and animals) that can be met by petroleum-derived products.

Drivers of change (a) to (c) could reduce demand for current petroleum-derived products, mainly energy products, while driver (d) could maintain demand provided suitable storage and technologies become available. Drivers (e) to (g) could increase demand for conventional and new petroleum products.

Consequently, the current petroleum industry can be expected to evolve, likely emerging as two distinct but connected subindustries, over the next decades. *Fig. 3.9.* and *Fig. 3.10.* respectively sketch the current and potential future petroleum industry.



**Fig. 3.9.** The current petroleum industry, its principal products, and their disposition.  
The width of the arrows symbolises the relative magnitude of what is produced

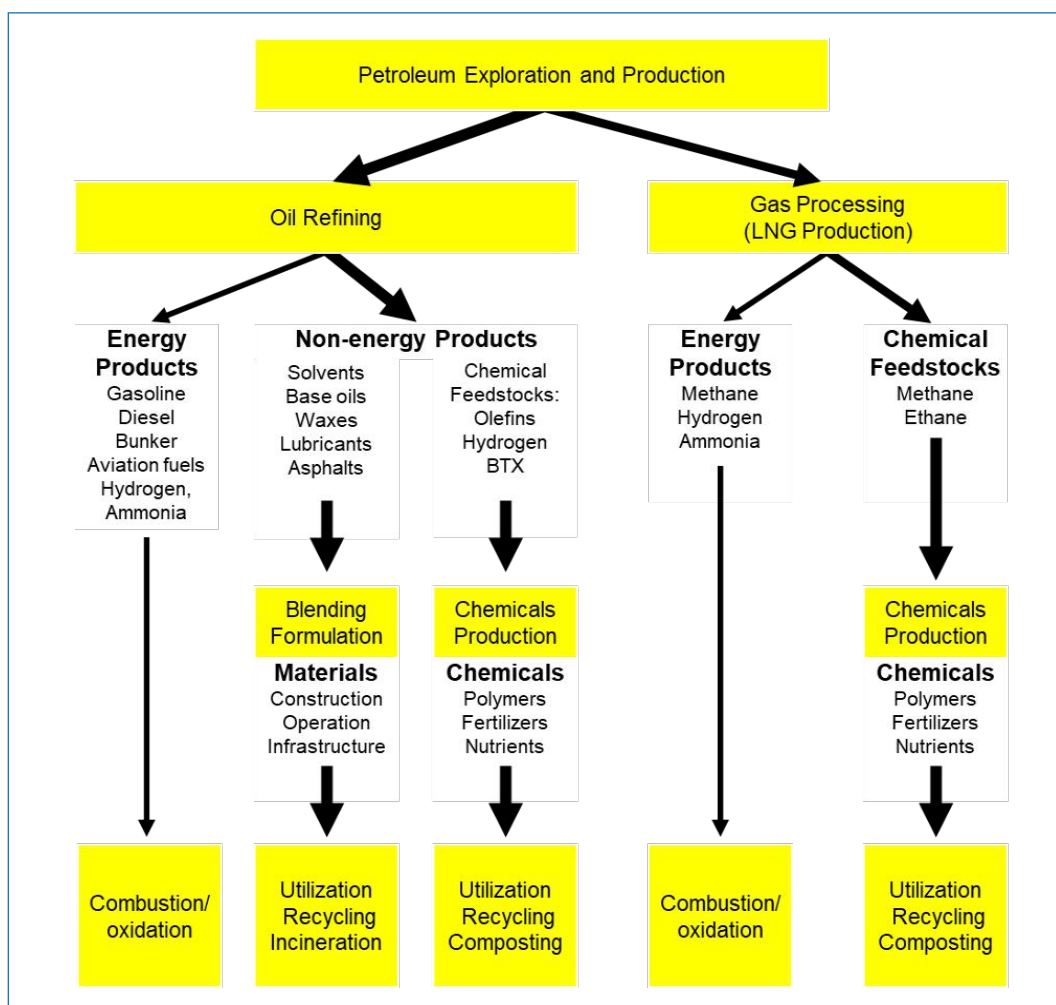
Five points to consider with respect to *Fig. 3.9.* are detailed below.

- These data are global figures, applying to the year 2019 or an earlier year. They are approximate, having been taken from different sources and, in some cases, recalculated using standard conversion factors. Data are indicative, with some deviation from other reported data to be expected.
- The global oil consumption of 4 423 Mt is equivalent to 90 million barrels per day (mbpd)<sup>15, 16</sup>.
- The natural gas consumption of 2 869 Mt is equivalent to 39 004 Gcm<sup>13</sup>
- Chemical feedstocks (olefins, hydrogen, BTX, etc.) require about 543 Mt of oil, equivalent to 12 mbpd (based on an equivalency of 0.124 tonnes per barrel of oil)<sup>17</sup>.
- The oil requirement for solvents, base oils, waxes, lubricants, and asphalts is 290 Mt.

<sup>15</sup> BP Statistical Review of World Energy (2021). <http://www.bp.com/statisticalreview>

<sup>16</sup> BP Approximate conversion factors (2021). <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-approximate-conversion-factors.pdf>

<sup>17</sup> IEA, The Future of Petrochemicals (2018). [https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The\\_Future\\_of\\_Petrochemicals.pdf](https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The_Future_of_Petrochemicals.pdf)



**Fig. 3.10.** The potential future petroleum industry, its principal products and their disposition.  
The width of the arrows symbolises the relative magnitude of what is produced.

In the future, one subindustry can be expected to produce mainly energy products, such as gasoline, diesel, and marine and aviation fuel for which there will be continued albeit potentially reduced demand. This subindustry may also produce new energy products, such as hydrogen, ammonia, and e-fuels. The other subindustry would mainly provide non-energy products to meet rising global demands for base chemicals, construction, and other industrial materials (housing, infrastructure, clothing, etc.), and nutrients for plants, animals, and possibly humans. Such needs, resulting from growing and more prosperous populations, are difficult to meet from natural resources alone with no adverse impacts on the biological environment and biodiversity. This subindustry may also be viewed as an extension of the present petrochemical industry.

The two subindustries will be linked by common reliance on petroleum resources, discovered and accessed by exploration and production respectively. They will share a common objective: the reduction (as much as practicable) of GHG emissions. The subindustries will also share and exchange intermediate feedstocks and products, recycled products, wastes, and utilities. Collaboration and harmonised operating plans between petroleum (i.e., oil and gas) and petrochemical industries will likely grow to reduce overall energy consumption, increase feedstock efficiencies, reduce the production of by-product fuels, and minimise process GHG emissions.

The oil and gas industry is and will continue to be the major provider of carbon-based fuels and carbon-based feedstocks for primary chemicals (see Fig. 3.9. and 3.10.).

Refineries will continue to play a paramount role as providers of fuels, petrochemicals, and feedstocks for the petrochemical industry (see also the Chemical Industry chapter). However, refineries must also confront a future in which demand for conventional fuels (mainly for road transport) decreases while demand for chemicals and chemical feedstocks grows at a rate likely exceeding 3% annually. Based on IEA data<sup>18</sup>, the share of oil for chemicals and for chemical industry feedstocks is estimated to increase from 14% presently to over 20% in 2030. This change will cause refineries to decrease the production of gasoline components and increase that of aromatics in catalytic reformers and light olefins (mainly propylene) in fluidised bed catalytic crackers<sup>19</sup>. The changes will require different catalysts, greater aromatic and olefin separation capacities, and additional hydrocracking capabilities. These changes may also allow refineries to process biological feedstocks and waste into bio-marine and bio-aviation fuels as well as lighter hydrocarbons and feedstock for olefin plants. However, such changes will limit the availability of heavy residues for products like asphalt binders. The market for the latter is projected to grow about 5% annually, primarily driven by infrastructure needs in developing countries.

### 3.1.1. Technologies

As suggested above, the future petroleum industry is expected to utilise, where feasible, more diversified feedstocks. Important examples of such feedstocks are:

- Plastics, currently produced at approximately 400 Mt/yr, with only a small portion being currently recycled.
- As the collection of waste plastics increases, some may not be suitable for physical recycling and need to be chemically recycled, pyrolysed or incinerated. In the latter cases, opportunities may arise for petroleum refineries to co-process these materials.
- Biomass unsuitable as food, organic waste (including animal fat and used cooking oil), municipal solid waste, and other low-carbon energy sources, arising from the application of circular economy principles.

The use of variable feedstocks poses important challenges, including the removal of impurities, reliability, and economies of scale. Many different technologies and pathways are now available to produce, for example, advanced liquid biofuels from biomass (e.g. via gasification, Fischer-Tropsch synthesis and the hydrotreatment of lipids). However, each pathway has distinct techno-economic characteristics, with process selection and operating conditions depending on the feedstock properties, integration with other operations, economics, and markets. A wide variety of approaches, involving both existing and novel ones, will therefore be required.

The coprocessing of crude oil with low carbon feedstocks is also a possibility when the latter are available on a large scale and at competitive prices<sup>20</sup>.

Examples of such schemes and technologies are currently being implemented in China and Saudi Arabia<sup>21</sup>. Electricity will likely become the principal energy source for process heating and steam generation in the petroleum industry. Large, steady supplies of low-carbon electricity will be needed, and low-carbon energy coupled with storage will be used where feasible. Nuclear energy (initially using fission, possibly from small modular nuclear reactors, and later fusion energy) may also become important but its impact will likely be small by 2050. Low-carbon electricity will not only reduce greenhouse gas emissions, but also increase energy efficiency and enable new process technologies, including organic electrochemistry. Carbon capture, utilisation and storage is expected to be applied in refining and chemical industries where possible. CCUS can also be coupled with bioenergy (BECCS) to allow for calculated 'negative' emissions. CCS and CCUS are two sets of basic technologies that will be adopted by the future petroleum industry where technically and economically feasible. Important issues of scale-up, reliability, and economic viability remain to be resolved.

Digitisation and artificial intelligence are expected to greatly contribute to the efficiency of both subindustries.

<sup>18</sup> IEA, The Future of Petrochemicals (2018). [https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The\\_Future\\_of\\_Petrochemicals.pdf](https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The_Future_of_Petrochemicals.pdf)

<sup>19</sup> From crude oil to chemicals: How refineries can adapt to shifting demand, McKinsey (2022). <https://www.mckinsey.com/industries/chemicals/our-insights/from-crude-oil-to-chemicals-how-refineries-can-adapt-to-shifting-demand>

<sup>20</sup> DROP-IN BIOFUELS: The key role that coprocessing will play in its production, IAE Bioenergy: Task 39 (2019). <https://task39.ieabioenergy.com/publications/>

<sup>21</sup> Crude Oil-to-Chemicals: Future of Refinery. <https://www.futurebridge.com/blog/crude-oil-to-chemicals-future-of-refinery/>

### 3.1.2. Products

In addition to current energy and non-energy products, it can be expected that the subindustry focused on energy products will increasingly produce low- or zero-carbon fuels, such as hydrogen, ammonia, and synthetic fuels combining low-carbon hydrogen and carbon. In addition, it will likely incorporate biological and recycled materials into feedstocks. Biological CO<sub>2</sub> sources can, in principle, also be used to synthesise bio-e-fuels, but they require independent and large energy sources at competitive prices.

The subindustry of the petroleum industry focused on non-energy products will continue to produce fertilisers and petrochemicals, but growth in the production of conventional plastics may be offset to some extent and where feasible by new types of biodegradable plastics. The latter will be fundamentally different from current plastics, likely mimicking biological polymers. Carbon fibres, advanced asphalt binders, and new construction materials also provide major, high-value growth opportunities for this subindustry.

## 4. Interactions between society, funding and human resources

We acknowledge that some of the following material is outside of the scope of the report, but we believe it is important since it provides context for a range of activities extending from the extraction of oil and gas out of reservoirs to oil refining and gas plant operations.

Climate change poses challenges to achieving the goals of more equitable social and economic policies, such as increased prosperity, sustainable growth and development and increased equity. A non-profit petroleum industry group, the International Petroleum Industry Environmental Conservation Association (IPIECA), and the World Bank, have been seeking to establish an agenda for research and action built on an enhanced understanding of the relationships between climate change and the key social dimensions of vulnerability, social justice, and equity.<sup>22, 23, 24</sup>

The United Nations Sustainable Development Goals (SDG) can serve as the basis for a roadmap and atlas (see *Fig. 3.11.*) for best practices for all industries, including oil and gas. The Goals are overarching goals, explaining the synergies and trade-offs that exist in key domains, where: decisions affect humanity's ability to realise the individual and collective aspirations for greater welfare and wellbeing; there is a need to build physical and social infrastructures for sustainable development; and there is a need to achieve the sustainable management of the environment and natural resources<sup>25</sup>.

<sup>22</sup> An Atlas. <https://www.ipieca.org/resources/awareness-briefing/mapping-the-oil-and-gas-industry-to-the-sustainable-development-goals-an-atlas-executive-summary/>

<sup>23</sup> <https://www.worldbank.org/en/topic/climatechange/brief/3-things-you-need-to-know-about-climate-finance>

<sup>24</sup> Energy Transition Outlook 2021. [www.dnv.com/et](http://www.dnv.com/et); [www.dnv.com](http://www.dnv.com)

<sup>25</sup> [https://discovery.ucl.ac.uk/id/eprint/10037715/3/Tomei\\_Manuscript%20-%20Energy%20and%20the%20SDGs\\_final.pdf](https://discovery.ucl.ac.uk/id/eprint/10037715/3/Tomei_Manuscript%20-%20Energy%20and%20the%20SDGs_final.pdf)

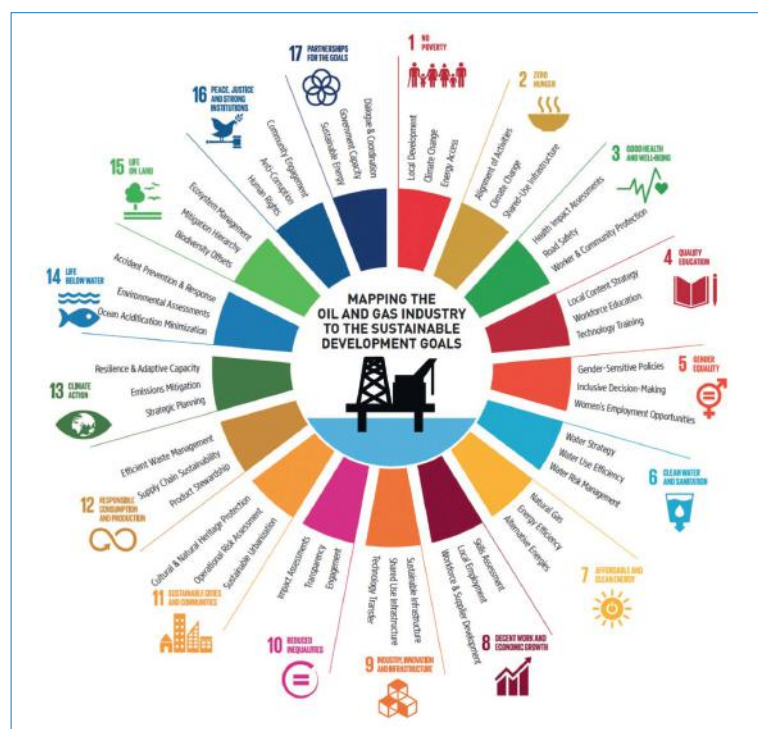


Fig. 3.11. Mapping the Oil and Gas Industry to the Sustainable Development Goals: An Atlas

IFC, IPIECA, UNDP Sustainable Development Goals, August 14, 2017, Page IX

[https://www.undp.org/publications/mapping-oil-and-gas-industry-sdgs-atlas?utm\\_source=EN&utm\\_medium=GSR&utm\\_content=US\\_UNDP\\_Paid-Search\\_Brand\\_English&utm\\_campaign=CENTRAL&c\\_src=CENTRAL&c\\_src2=GSR&gclid=Cj0KCQjwk5ibBhDqARisACzmGLRuvyIgh2PQLLwVSIXrY-Is-WyR8PwGb8XNUx\\_NluJ1xNF-3n3LiaUaAjHPEALw\\_wcB](https://www.undp.org/publications/mapping-oil-and-gas-industry-sdgs-atlas?utm_source=EN&utm_medium=GSR&utm_content=US_UNDP_Paid-Search_Brand_English&utm_campaign=CENTRAL&c_src=CENTRAL&c_src2=GSR&gclid=Cj0KCQjwk5ibBhDqARisACzmGLRuvyIgh2PQLLwVSIXrY-Is-WyR8PwGb8XNUx_NluJ1xNF-3n3LiaUaAjHPEALw_wcB)

### List of Sustainable Development Goals

- Goal 1:** End poverty in all its forms everywhere. Integrate into core business; collaborate and leverage;
- Goal 2:** End hunger, achieve food security and improved nutrition and promote sustainable agriculture;
- Goal 3:** Ensure healthy lives and promote well-being for all at all ages;
- Goal 4:** Ensure inclusive and equitable quality education and promote lifelong learning opportunities for All;
- Goal 5:** Achieve gender equality and empower all women and girls;
- Goal 6:** Ensure availability and sustainable management of water and sanitation for all;
- Goal 7:** Ensure access to affordable, reliable, sustainable, and modern energy for all;
- Goal 8:** Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all;
- Goal 9:** Build resilient infrastructure, promote inclusive and sustainable industrialization and foster Innovation;
- Goal 10:** Reduce inequality within and among countries;
- Goal 11:** Make cities and human settlements inclusive, safe, resilient, and sustainable;
- Goal 12:** Responsible consumption and production—ensure sustainable consumption and production patterns;
- Goal 13:** Take urgent action to combat climate change and its impacts;
- Goal 14:** Conserve and sustainably use the oceans, seas, and marine resources for sustainable development;
- Goal 15:** Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably Manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss;
- Goal 16:** Promote peaceful and Inclusive Societies for Sustainable Development, Provide Access to Justice for All and Build Effective, Accountable, And Inclusive Institutions at All Levels;
- Goal 17:** Strengthen the Means of Implementation and Revitalize the Global Partnership for Sustainable Development.

Delivering on SDG7 – ensuring access to affordable, reliable, sustainable, and modern energy for all – requires an understanding of how energy systems lie at the foundations of social and economic development and affect the achievement of all SDGs. The SDGs represent a framework for examining these linkages and making decisions that balance them effectively. Action is required to change energy systems in a way that will take better account of how climate variables interact with other drivers of vulnerability.<sup>26, 27</sup>

It is widely recognised that interactions between society, funding and human resources need to be equitable and just in order to be sustainable globally over the long term. A just transition is an integral part of the Paris COP 21 Agreement, and it involves balancing sustainability priorities, such as the SDGs, across all regions and sectors. Crucially, it focuses beyond industries and financial markets on societies and people affected by them. A just transition is both a risk and enabler of an accelerated energy transition. For governments, enabling a just transition is a prerequisite for achieving policy targets: transition initiatives will fail in the absence of sustained support from the most part of society. Recognising this, governments are taking action.<sup>28</sup>

The European Union (EU) has launched its Just Transition Mechanism as part of the European Green Deal. The mechanism aims to mobilise EUR 65-75 billion over the period 2021-2027 in the most affected regions in Europe to alleviate the socioeconomic impact of the transition, particularly to create and safeguard jobs. In North America, mechanisms are in place to reduce the cost to taxpayers and consumers. Canada created a Just Transition Taskforce in 2018, and revenue from its CO<sub>2</sub> tax will be recycled and returned to the population ('People's payout') on a per capita basis. It is probable that, in Canada, not all funds collected will be recycled to the population, at least not directly. Significant amounts will be invested into research, development, and the deployment of technologies that reduce GHG emissions.

In the United States, California's Emissions Trading System (ETS) compensates all households with a 'Climate Credit' on utility bills, and some ETS revenue goes to a GHG Reduction Fund for low-carbon technologies and mitigation. The capacity of companies to achieve a just transition - both environmental and social - is increasingly among the criteria considered by a growing number of investors. This includes looking at the dialogue a company has with stakeholders such as trade unions and local communities, its track record of successful transformations, and such behaviours as paying taxes that are linked to license to operate. That is, when applying frameworks for sustainable investment, financiers calculate the abatement of emissions, but also the benefits to societies and people from climate interventions. Specifically, if government subsidies are involved in a project, there are likely to be expectations for the project to deliver jobs and long-term infrastructure. This includes getting the supply chain to work in many cases using domestic companies, labour, and equipment. For energy companies, particularly providing utilities or directly serving the public, a just transition is also about ensuring benefits for consumers and bringing all parts of society along. This offers opportunities if the right business model can be found.<sup>29, 30</sup>

#### 4.1. Sustainable Development Goals (SDGs)

A just energy transition will seek to find solutions that also provide co-benefits to the SDGs. These include economic development and employment, energy access, cleaning the oceans, and alleviating air pollution, all of which can greatly benefit from an accelerated transition. For all these challenges, the pairing of potential solutions with incentives for energy efficiency can yield significant benefits<sup>31, 32</sup>. This will require the oil and gas industry to map its objectives to assist in delivering the SDGs as shown in *Fig. 3.11*.

#### 4.2. Workforce

The International Labour Organization (ILO) estimates that shifting to a greener economy by 2030 could result in the net creation of 18 million jobs globally. This is the result of 24 million jobs being created while 6 million are lost. This shows the significant employment and economic benefits of the energy transition, but also the

<sup>26</sup> The World Bank: Understanding Poverty. [www.worldbank.org/climate](http://www.worldbank.org/climate)

<sup>27</sup> Waage, J. et al. Governing the UN sustainable development goals: interactions, infrastructures, and institutions. *Lancet. Glob. Heal.* 3, e251-2 (2015).

<sup>28</sup> Brew-Hammond, A. Energy: The Missing Millennium Development Goal. 35-43 (2012). doi:10.1007/978-94-007-4162-1\_3

<sup>29</sup> <https://www.worldbank.org/en/topic/climatechange/brief/3-things-you-need-to-know-about-climate-finance>

<sup>30</sup> Financing the Energy Transition; Energy Transition Outlook 2021. [www.dnv.com/et](http://www.dnv.com/et); [www.dnv.com](http://www.dnv.com)

<sup>31</sup> Nilsson, M., Griggs, D. & Visbeck, M. Map the interactions between Sustainable Development Goals. *Nature* 534, 320-322 (2016)

<sup>32</sup> Sovacool, B. K. & Dworkin, M. H. Global Energy Justice. *Global Energy Justice: Problems, Principles, and Practices* (2014). doi:10.1017/CBO9781107323605

danger of lost jobs. Reskilling and redeploying the workforce should be a key focus of oil and gas companies as well as governments in oil and gas producing countries. There are synergies to be found in switching from oil and gas to offshore wind, carbon capture and storage (CCS) and hydrogen, for example, which could reduce the impact of abrupt changes on the workforce while offering a competitive edge in certain fields. One example in Norway would be people switching from working on oil and gas exploration to contributing to the Northern Lights project – the world’s first open-source transport and storage infrastructure to deliver carbon storage as a service. Equinor, Shell and Total Energies are equal joint venture partners in Northern Lights<sup>33</sup>. All three partners have contributed people, experience and financial support.

### 4.3. Health

The World Health Organization<sup>34</sup> estimates that, between 2030 and 2050, climate change will cause approximately 250 000 additional deaths globally per year. The additional costs are rarely accounted for in energy modelling. With air pollution being arguably the most recognised danger to health from emissions other than GHG emissions, the pursuit of clean air is already mounting worldwide. This is exemplified by China’s Action Plan for Winning the Blue-Sky War and efforts to cap coal use, and India’s National Clean Air Programme with emission control standards on coal power plants. These initiatives, and others such as reducing flaring, addressing electricity supply, electricity cost, and equipment cost, provide significant co-benefits in reducing emissions and air pollution. A just transition takes a wider perspective on these and premature deaths due to health issues, looking for example at the cost of asthma to the health system, and comparing the cost of treatment over a person’s lifetime with the cost of taking measures to reduce either the incidence or effects of asthma. Such measures could win on cost, without even considering the health benefits for people and the co-benefit of reducing emissions. The key is to find business models to fund these types of changes without passing significant costs on to the consumer.

Otherwise, it will once again be the disadvantaged people who pay disproportionately the cost, whether health or financial<sup>35, 36</sup>.

### 4.4. Mobility

People in all income level neighbourhoods should be able to benefit from cleaner air, including from the benefits of increasing the number of zero-emission vehicles such as electric vehicles (EVs). To address this, governments, organisations providing utilities, and finance institutes are seeking to support the funding of EVs and charging infrastructure access for all. There will of course still be a range of EV adoption rates, both locally and internationally. These will be impacted by disposable income<sup>37</sup>, government policies and the level of grid infrastructure development. It will be nonetheless important to support equitable access for technologies such as EVs, which have a significant impact on the energy transition and the health and wellbeing of people in industrial and densely populated areas. For example, the adoption of EVs can be comparable to that of mobile phones: mobile phones initially required high capital and operating costs, and their use was limited geographically. This has changed and is largely due to advances in technology, mass production and mass adoption. We expect advances in EV technologies, and the infrastructure supporting their use, to lower costs and make EVs more affordable.

<sup>33</sup> <https://northernlightsccs.com/news/northern-lights-launches-company-dedicated-to-co2-transport-and-storage/>

<sup>34</sup> [https://www.who.int/health-topics/climate-change#tab=tab\\_1](https://www.who.int/health-topics/climate-change#tab=tab_1) World Health Organization

<sup>35</sup> <https://www.worldbank.org/en/topic/climatechange/brief/3-things-you-need-to-know-about-climate-finance>

<sup>36</sup> Climate Change. [https://www.who.int/health-topics/climate-change#tab=tab\\_1](https://www.who.int/health-topics/climate-change#tab=tab_1) World Health Organization

<sup>37</sup> <https://www.noemamag.com/the-human-cost-of-moving-away-from-fossil-fuels>

#### 4.5. Adaptation and resilience

Mitigation alone will not stop the impact of global warming on people and societies. Adaptation and resilience must be built into systems and infrastructures to moderate harm from the forecasted increasingly severe climate effects. The cost of natural disasters keeps rising worldwide. It is, thus, not only about net zero; it is about climate resilience as well. Climate resilience is also a just and equitable transition issue. The average CO<sub>2</sub> emissions per person in Sub-Saharan Africa are approximately equivalent to 1/20<sup>th</sup> of such emissions in North America; yet, developing countries<sup>38</sup> and poorer communities are most vulnerable to the climate crisis. The greatest challenges they face are developing and financing infrastructure, and building capacities to absorb the impact<sup>39</sup>.

Since the ambitious goals of the Paris Agreement are unlikely to be met and since the Net Zero by 2050 scenario seems very ambitious, it would be realistic to suggest that the adaptation and reinforcement of critical infrastructure for the forecasted increasing impact of climate change is an important issue. Of course, investing in the reinforcement of infrastructure has also many other benefits for people and societies<sup>40</sup>, and should contribute to lower emissions in such cases as, for example, investing in more mass transit, burying power lines to reduce power failures, or reinforcing infrastructure and making it more resilient against the impacts of severe storms.

## 5. Key Messages and Recommendations

### Key Messages

1. Today, the world relies heavily on fossil fuels today. Fossil energy sources now provide more than 84% of global primary energy consumption (PEC), with oil and natural gas being the largest providers as they account for more than 57%. The use of crude oil and natural gas has been increasing worldwide, especially in less developed countries, and will likely continue doing so in the near- to medium-term future, which is the horizon of this report. The outlook for the long-term future (i.e., the future beyond 2040 or so) is less certain and may involve a decline in the use of fossil fuels for energy production.
2. Cumulative investments in the oil and gas industry amount to trillions of dollars, and facilities have life spans of decades. This makes it economically and operationally challenging to affect major changes at a rapid pace and on a global scale.
3. The increasing use of fossil fuels is responsible for the main share of growing global greenhouse gas (GHG) emissions. There is rising political, social and financial pressure on all companies, including petroleum companies, to participate in the transition needed to achieve the ambitious goal of net-zero GHG emissions by 2050.
4. Methane flaring and fugitive methane emissions contribute significantly to greenhouse gas emissions from petroleum production, transport, and refining/processing. Methane concentrations in the atmosphere, in part related to the oil and gas industry, are rising fast, and methane is a much more potent GHG than CO<sub>2</sub>.
5. Energy transition and decarbonisation will remain dominant issues throughout the world, driven by energy and climate policies, environmental and economic concerns, changes in public perceptions, and the attitudes of investors. Significant change is however unlikely to occur without any changes to global demand patterns, regulations in major consuming countries and the availability of cost-effective and sustainable alternatives to oil and gas.
6. The oil and gas industry will need to adapt to demand for low greenhouse gas production and products. In the long term, total demand for oil and natural gas may be lower than it is at present. Two interrelated petroleum subindustries are expected to emerge: one focused on specialty and low-carbon energy products, and the other on non-energy products. The two subindustries may process less oil and gas in total but potentially reach higher economic value, and they would meet sustainability expectations. The number of people employed by such two future subindustries may decline over time, but with job skills increasing.

<sup>38</sup> <https://dochub.com/goddy-igwe/pqb0g5YRqy9dN5DRJ2nx67/world-bank-report-1988-pdf?dt=5zDPHXidBLUCcWgZR7TH>

<sup>39</sup> [https://www.ft.com/content/6ee697a5-fe5c-473c-9b0c-9b68dd200288?accessToken=zwAAAYH\\_ZFFdkc9u5pel\\_lxHPNOBJto3SACIA.MEUCIQComTyeWhVacNlyzCqsZsESpVGTISQBDzLSCWXcp-xCQlgO9-x41sU9fU-STBT72LdV-2ji35Ms4sUhrvKe4vBiA&sharetype=gift?token=3cd02569-d1cb-4039-8374-50774e6716f0](https://www.ft.com/content/6ee697a5-fe5c-473c-9b0c-9b68dd200288?accessToken=zwAAAYH_ZFFdkc9u5pel_lxHPNOBJto3SACIA.MEUCIQComTyeWhVacNlyzCqsZsESpVGTISQBDzLSCWXcp-xCQlgO9-x41sU9fU-STBT72LdV-2ji35Ms4sUhrvKe4vBiA&sharetype=gift?token=3cd02569-d1cb-4039-8374-50774e6716f0)

<sup>40</sup> The Human Cost of Moving Away from Fossil Fuels. <https://www.noemamag.com/the-human-cost-of-moving-away-from-fossil-fuels>

## Recommendations

### 5.1. Strong emphasis on reducing methane flaring and fugitive methane emissions in all phases of oil and gas production, transport, and refining / processing

The most pressing, and perhaps the most achievable and most cost-effective action for oil and gas producing countries and companies, is to focus on reducing methane emissions. Technologies to abate methane are available and many are already cost effective. The IEA estimates that 45% of emissions can be abated at no cost under 2021 gas prices. A reduction of 60% or more by 2030 should also be possible if the proper measures are enacted.

### 5.2. Exploring additional steps to lower CO<sub>2</sub> emissions

Although most CO<sub>2</sub> emissions from oil and gas result from their consumption, which is outside the scope of our report, we recommend exploring additional steps to lower CO<sub>2</sub> emissions, from the exploration and production sectors through the reduction of flaring, the implementation of efficiency improvement, and new technologies. We also recommend exploring the increased electrification of the oil and gas industry. Electrification may play a growing part as a substitute for the direct heating and cooling of process streams. We recommend that operators of oil and gas facilities consider switching to electric options where feasible and where they are likely to have a positive impact on lowering GHG emissions.

### 5.3. Greater emphasis on using and improving Life Cycle Assessment (LCA) models

LCA models can help determine whether actions taken to reduce GHG emissions are effective and sustainable. Attributional LCA models have been used by regulators, but they do not capture all the rebound effects, unknowns, uncertainties, or unintended consequences. Consequential LCA models are then increasingly used to try to add some of these indirect and follow-up effects but their long-term prediction accuracy and completeness remain to be proven. We recommend that governments and other stakeholders promote and use LCA and related models to avoid prevalent 'greenwashing' and marketing claims that have been shown to have no impact, or occasionally negative impacts, and that they balance societal needs.

### 5.4. Continued evaluation and development of the potential of CCUS opportunities for oil and gas operations

Carbon Capture, Utilisation and Storage (CCUS) technologies are already receiving much attention to reduce the impacts of global climate change. They could play an important role in offsetting GHG emissions resulting from oil and gas industry operations. Although recent investments and technical progress are encouraging, the planned projects, even if successful, would fall well short of delivering the 1.7 billion tonnes of CO<sub>2</sub> capture capacity that should be deployed by 2030 according to the Net Zero by 2050 scenario. Many questions remain to be answered, including the potential scale of deployment, efficiency and cost of CCUS projects, and the stability and ultimate fate of captured CO<sub>2</sub>, whether in storage or intended to be converted to other products.

### 5.5. Increased investments in R&D and training

It is necessary to continuously support R&D to address the scale-up and long-term operability issues of promising technologies. Fostering R&D and training, with sustainable operations as ultimate goals, is in the interest of both the petroleum industry and society. Shared funding between industry and governments is therefore justified. Such funding should 'de-risk', as it were, the introduction of new technologies, accelerate their wide adoption, and, very importantly, prepare people for the new economy characterised by net-zero carbon emissions.

## List of abbreviations and acronyms

---

<b>AI</b>	Artificial Intelligence
<b>ALCA</b>	Attributional LCA
<b>APS</b>	Announced Pledges Scenario
<b>BECCS</b>	Bioenergy with Carbon Capture
<b>BTX</b>	Benzene, Toluene, Xylene
<b>CAETS</b>	Council of Academies of Engineering and Technological Sciences
<b>CCS</b>	Carbon Capture and Storage
<b>CCUS</b>	Carbon Capture Utilisation and Storage
<b>CHP</b>	Combined Heat and Power
<b>CLCA</b>	Consequential LCA
<b>CO<sub>2</sub></b>	Carbon Dioxide
<b>CORSIA</b>	Carbon Offsetting and Reduction Scheme for International Aviation
<b>DMS</b>	Dynamic Matrix Control
<b>EMS</b>	Energy Management Systems
<b>ETS</b>	Emissions Trading System
<b>EU</b>	European Union
<b>EV</b>	Electric Vehicle
<b>GDP</b>	Gross Domestic Product
<b>GHG</b>	Greenhouse Gas
<b>HFC</b>	Hydrofluorocarbon
<b>IAM</b>	Integrated Assessment Model
<b>ICAO</b>	International Civil Aviation Organization
<b>IEA</b>	International Energy Agency
<b>ILUC</b>	Induced Land Use Change
<b>IOGP</b>	International Association of Oil and Gas Producers
<b>IPIECA</b>	International Petroleum Industry Environmental Conservation Association
<b>LCA</b>	Life Cycle Assessment
<b>LDAR</b>	Leak Detection And Repair
<b>LED</b>	Light Emitting Diode
<b>LNG</b>	Liquefied Natural Gas
<b>LUC</b>	Land Use Change
<b>MRV</b>	Monitoring, Reporting and Verification
<b>NG</b>	Natural Gas
<b>NGO</b>	Non-Governmental Organisation
<b>NZE</b>	Net-Zero Emissions
<b>OGCI</b>	Oil & Gas Climate Initiative
<b>PEC</b>	Primary Energy Consumption
<b>R&amp;D</b>	Research and Development
<b>SDG</b>	Sustainable Development Goal
<b>SLCA</b>	Societal LCA
<b>STEPS</b>	Stated Policies Scenario

---

## CHAPTER 4. CHEMICAL INDUSTRY

### Members of the Working Group

**Behrendt Frank**, Germany

**Bravo Lopez Manuel**, Spain

**Coker Olufunmi**, Nigeria

**Haslett Andrew**, United Kingdom

**Hofmann Rita**, Switzerland

**Igwe Godwin J**, Nigeria / United States of America

**Matlosz Michael**, France (Co-chair)

**Vignart Oscar**, Argentina (Co-chair)

## Table of Contents

---

<b>Executive Summary</b> .....	155
<b>1. Introduction</b> .....	156
<b>2. Current situation</b> .....	157
<b>3. Value chain</b> .....	158
<b>4. Ethylene and propylene</b> .....	159
4.1. Ethylene .....	159
4.2. Steam cracking .....	159
4.3. Propylene .....	159
4.4. Options for decarbonisation .....	160
<b>5. Ammonia</b> .....	161
5.1. Manufacturing process and current use .....	161
5.2. Use and projection for future use .....	161
5.3. Reducing carbon greenhouse emissions .....	162
<b>6. Methanol</b> .....	163
6.1. Reducing carbon greenhouse emissions .....	163
<b>7. Future scenarios</b> .....	163
7.1. Extrinsic factors and challenges .....	163
7.2. Increased process energy requirements for electrification and CCUS .....	164
7.3. Bio-sourcing the process energy for the CPI: perspectives and limits .....	164
7.4. Charting individual paths .....	165
7.5. Technologies, assets and skills .....	165
<b>8. Key Messages / Recommendations</b> .....	166
8.1. Major high-tonnage chemical production will not disappear in the next 10 to 20 years .....	166
8.2. The decarbonisation of the chemical process industries (CPI) can begin immediately through proper deployment of currently available technologies and improved feedstock efficiency .....	166
8.3. Carbon capture, utilisation and storage will be required .....	166
8.4. Accelerate the reuse, reduction and recycling of carbon-based materials (in particular plastics) .....	166
8.5. Reduce the use of nitrogenous fertilisers through improved agricultural practices .....	166
8.6. Electrification of process heating with low-carbon electricity .....	167
8.7. Large-scale development of low-carbon hydrogen production (in particular for ammonia synthesis) .....	167
8.8. Increase the use of ethane for ethylene production and replace coal with natural gas for methanol production .....	167
<b>List of abbreviations and acronyms</b> .....	168

## Executive Summary

The chemical sector comprises thousands of complex value chains. Most of them start with the production of one or more of seven primary chemicals: ethylene, propylene, benzene, toluene and xylenes – known as high-value chemicals (HVC) – and ammonia and methanol. These seven primary chemicals are the building blocks of the chemical industry. What makes these products special is that the fossil hydrocarbons production consumes (oil, gas and coal) are mainly employed as feedstock. They provide the carbon and hydrogen needed to build these primary chemicals. For this reason, the chemical industry has the highest energy intensity of any industrial sector in terms of fossil hydrocarbon consumption. Its CO<sub>2</sub> emission intensity is however much lower since the majority of the hydrocarbons consumed are not burned but rather incorporated into the primary chemicals produced.

The chemical sector is responsible for 15% of the total greenhouse gas (GHG) emissions (8.4 Gt CO<sub>2</sub>) of the industrial sector. With 5%, ammonia is the largest contributor of all the chemicals. The sector is very capital-intensive, as it involves substantial long-term physical assets and infrastructures, and is present in all geographical regions of the world, with particularly strong developments in the last 20 years in Asia, mainly China. Chemical production has been growing with increasing worldwide gross domestic product (GDP) over the last 20 years. For some products, such as plastics, the growth rate of production is indeed higher than GDP growth. Over the next 20 to 30 years, economic and population growth will continue to push demand.

The present chapter focuses on the analysis of GHG emissions for the production of the four highest-tonnage products (ethylene, propylene, ammonia and methanol). These four primary chemicals have been chosen for the very large production volumes they involve and their resulting major impact on the overall decarbonisation effort. The scope of this chapter has been mostly limited to the manufacturing processes of these chemicals, recognising that additional emissions are associated with the use of products derived from such primary chemicals once they reach the market. Changes in end-product uses dictated by regulation or product alternatives will also impact production volumes for these primary chemicals over time.

As an industry that is particularly complex, integrated, intensive in capital and skills and provides many long-term assets, the chemical sector faces enormous challenges in the transition to net zero carbon. Not only are the changes to implement technically important but they will have profound economic and social consequences as well. There is no single or simple solution available today to decarbonise the chemical industry, yet there are nevertheless important steps that can immediately guide the industry towards its decarbonisation goals. Such steps include the following:

- feedstock efficiency: increasing ethane use in steam crackers for ethylene production, for example, or replacing coal by natural gas in methanol production;
- reusing products (mainly plastics) and recycling waste;
- carbon capture, utilisation and storage (CCUS): capturing exhaust gases, applicable in many processes;
- electrification of process heating (using low-carbon electricity);
- low-carbon hydrogen (for example green hydrogen or blue hydrogen with CCUS): applicable to several processes, including ammonia synthesis.

## 1. Introduction

The chemical industry transforms natural resources (fossil hydrocarbons, natural products and minerals) into materials that other industries and final consumers use. The industry consists of numerous value chains that produce thousands of products (more than 70 000), covering a large number of industrial sectors. Most chemical products are used in the manufacture of consumer goods and industrial items, and as inputs to agriculture and construction. Although more than 90% of manufactured goods are dependent on the chemical industry, only a small number are marketed directly to final consumers. Society's dependence on chemicals is clear from the growth in their demand, which follows GDP growth, and certain chemicals, such as plastics, grow at higher rates than many other bulk materials, including steel and cement<sup>1</sup>.

The chemical industry is the largest consumer of fossil hydrocarbons of all industrial sectors but ranks only third in terms of direct CO<sub>2</sub> emissions, behind cement and steel. This difference stems from the fact that roughly half of the fossil hydrocarbons consumed in the chemical industry are used as feedstock (carbon and hydrogen sources) and not as fuel. Such feedstock contains the basic hydrocarbon groups of a limited number of primary chemicals, referred to as petrochemicals, from which most other chemical products are derived. These primary chemicals are light olefins (ethylene, propylene) and aromatics (benzene, toluene and xylenes, known as BTX), jointly referred to as high-value chemicals (HVC), along with ammonia and methanol. They are indeed mainly derived from petroleum products, such as ethane and naphtha, or natural gas, although coal is still used to a limited extent to produce ammonia and methanol.

As indicated above, the consumption of fossil hydrocarbons in the chemical process industries (for HVC as well as for ammonia and methanol) serves two quite different purposes. First, fossil hydrocarbons may be employed as raw-material feedstock to build the primary chemicals. In this regard, there may be CO<sub>2</sub> emissions related to the poor selectivity or the undesired production of secondary by-products resulting from the chemical reactions themselves. In the case of ethylene production from ethane in a steam cracker, for example, methane is often produced in substantial quantities as a by-product that is burned in the process, thereby generating CO<sub>2</sub>. The production of ammonia from natural gas is another example, since the methane in the natural gas used to generate the hydrogen for ammonia synthesis produces not only hydrogen but also CO<sub>2</sub>.

The second purpose of fossil hydrocarbons is their direct use as fuel for process heating. In that case, the CO<sub>2</sub> generated is related to the power consumed by the process, regardless of the nature, selectivity or by-products of the chemical reactions involved.

The petrochemical industry, the branch of the chemical industry employing fossil hydrocarbons as a material feedstock, accounts for 90% of the demand for fossil hydrocarbons in the chemical industry as a whole. The petrochemical industry represents, however, only two thirds of the energy consumption of the chemical sector, since a substantial portion of the fossil hydrocarbons is not used for combustion but rather remains embedded in the chemical products produced.

Improving feedstock transformation efficiency (including the selectivity of chemical reactions) and optimising energy consumption (and energy efficiency) are therefore the key elements to focus on in order to take action to decarbonise the chemical industry.

The major challenge facing operators in the petrochemical industry specifically is to reduce CO<sub>2</sub> and other GHG emissions in the production of primary chemicals. The production of primary chemicals constitutes more than 60% of the total fossil-hydrocarbon feedstock demand in the industry and the production processes for primary chemicals, due to their large heat and power requirements, emit substantial amounts of CO<sub>2</sub>.

The priority focus for decarbonisation is to improve feedstock efficiency and replace fossil-fuel energy to the largest extent possible, in addition to increasing the reuse of materials and the recycling of waste. These are the key issues addressed in this chapter.

<sup>1</sup> IEA: The future of petrochemicals, towards more sustainable plastics and fertilizers (2018). <https://www.iea.org/reports/the-future-of-petrochemicals>

## 2. Current situation

Demand for chemical products is based on demand for a large variety of manufactured goods that require chemicals for their production. Demand for primary chemicals, which is a good indicator of the overall demand in the chemical sector, has strongly increased in recent years and is expected to continue doing so over the next two to three decades.

Demand for high-value chemicals (HVC), the key building blocks of plastics, is being propelled by an increase in demand for plastics in sectors such as packaging, construction and automobiles. Demand grew at an annual rate of 3.5% over the period from 2000 to 2020<sup>2</sup>, and growth is expected to continue at a similar rate from 2020 to 2030, pushed by consumption in developing countries. In many developing countries, the annual consumption of plastics is as low as 4 kg per capita annually, but growth rates in those countries are high. In developed countries, plastics consumption ranges from 55 to 80 kg per capita, although in some mature economies consumption has stabilised at around 60 kg per capita. Therefore, increased demand over the next 20 to 30 years will be driven not only by economic but also by population growth.

Oil is the main feedstock for HVC production, whether it takes place in refineries (as do 40% of propylene and 80% of BTX globally)<sup>3</sup> or through the cracking of petroleum products, as ethane and naphtha, in steam cracking plants. The production of HVC and other petrochemicals accounts for as much as 14% of global demand for oil products and amounts to a substantial proportion of demand for natural gas<sup>4</sup>.

Ammonia is another primary chemical, mainly used in the production of nitrogenous fertilisers, of which urea and ammonium nitrate are the most important. The production of ammonia requires hydrogen, which can be obtained from fossil hydrocarbons or generated by electrolysis of water using low-carbon electricity. Although the hydrogen required for most ammonia production today is generated by the reforming of natural gas, production units based on low-carbon hydrogen are being developed in some countries. Demand for ammonia has been stable over the last few years, at a level of about 180 million tonnes per year, as a result of increased efficiency in the use of fertilisers in developed countries. Such demand is nevertheless expected to increase evenly across the world in the coming years, at an annual rate of about 2%.

Methanol is also a primary chemical in the chemical industry and it is experiencing one of the highest demand growth rates. It is used in the production of formaldehyde, which is employed for the production of special plastics and coatings, and also as a liquid-fuel component either directly as methanol or indirectly after being converted to ether (e.g. Methyl tert-Butyl Ether (MTBE)). Methanol demand grew at an average annual rate of about 7% over the period from 2000 to 2020, and demand growth is expected to continue doing so at the same rate over the near term: despite an expected decrease in its use for gasoline blending. Moreover, it can be used as an intermediate for olefin production, substituting for oil products.

Compliance with net zero or other GHG emission targets will expand the use of ammonia and methanol as energy carriers, since they can be produced from low-carbon energy sources, such as low-carbon hydrogen. In particular, the use of ammonia for the storage of low-carbon hydrogen and as an energy carrier is likely to significantly increase for certain applications, such as marine engines.

<sup>2</sup> IEA: Chemicals tracking report, Nov. 2021. <https://www.iea.org/reports/chemicals>

<sup>3</sup> IEA: The future of petrochemicals, towards more sustainable plastics and fertilizers (2018). <https://www.iea.org/reports/the-future-of-petrochemicals>

<sup>4</sup> IEA: The future of petrochemicals, towards more sustainable plastics and fertilizers (2018). <https://www.iea.org/reports/the-future-of-petrochemicals>

### 3. Value chain

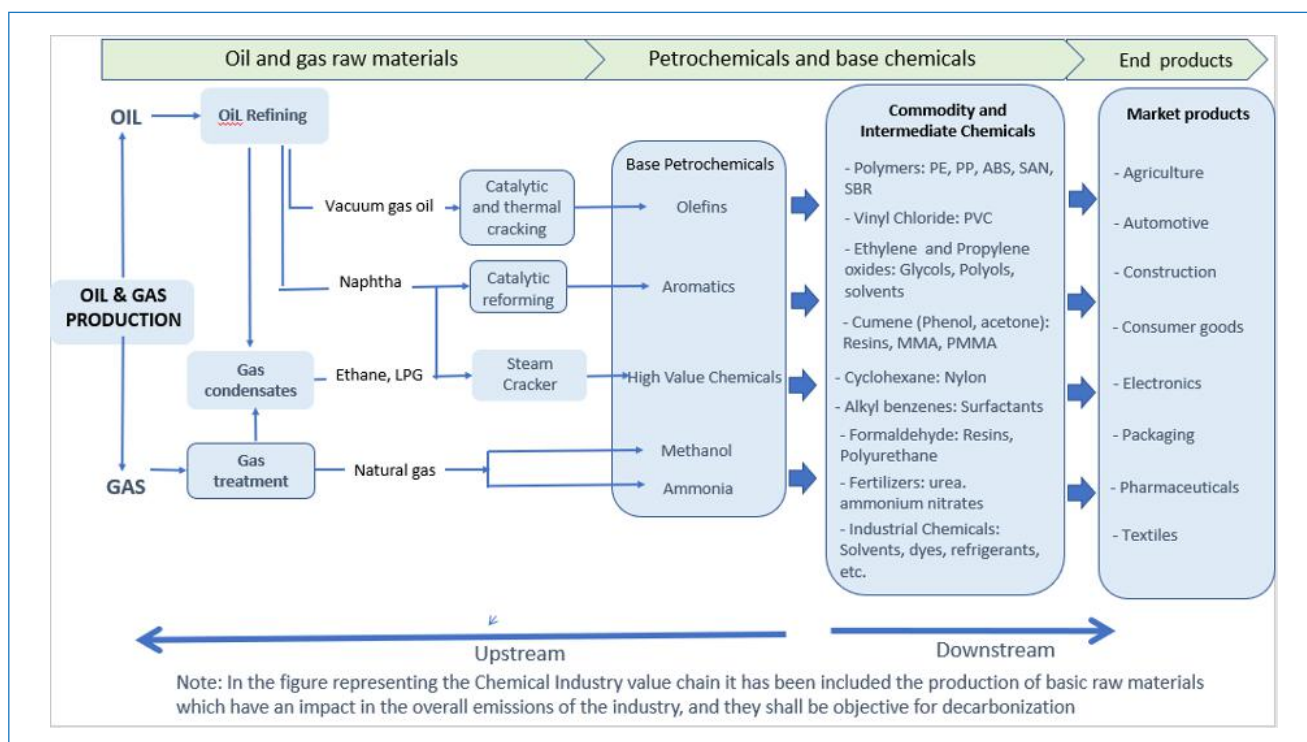
The chemical industry value chain is composed of a series of chemical transformation steps that are performed to deliver market-valuable chemical products. A chemical company operates in one or several of these chemical transformation steps, which are performed in order. At each step in the value chain, the market value of the products is increased (*Fig. 4.1.*), and the energy involved in the previous steps is embedded in the products placed on the market.

Many players in the raw materials and petrochemical sectors are integrated chemical or oil and gas companies that operate integrated projects in order to maximise energy efficiency, reduce costs and optimise the globalisation of the supply chains.

The first step in the value chain concerns the production of basic primary chemicals from raw-material feedstocks. The second step of the value chain includes the following elements.

- Intermediates: produced from the primary chemicals, they are to be employed as starting materials for various industries to manufacture a wide variety of commercial products.
- Polymers: produced by the polymerisation of basic olefins and aromatics in large plants through continuous or batch processes, polymers are principally used to make plastic goods and constitute about 80% of the chemical industry's production output.
- Fine chemicals and specialties: fine chemicals are complex chemicals produced in smaller quantities than those of groups a) and b). They are produced in multipurpose plants, and are starting materials for specialties.

All of the chemicals in the chemical sector supply chain are used directly or form part of the final products in many industrial subsectors as key components providing specific characteristics. The industrial subsectors involved are very numerous and include those listed in *Fig. 4.1.*



**Fig. 4.1.** The chemical industry value chain [1]

Source of right-hand part of diagram:

[https://iea.blob.core.windows.net/assets/bec4ef3a-8876-4566-98cf-7a130c013805/The\\_Future\\_of\\_Petrochemicals.pdf](https://iea.blob.core.windows.net/assets/bec4ef3a-8876-4566-98cf-7a130c013805/The_Future_of_Petrochemicals.pdf)

## 4. Ethylene and propylene

### 4.1. Ethylene

Ethylene is the lightest olefin and a key building block for polymers and other chemical products that are essential for the manufacturing industry. Ethylene is the largest produced petrochemical worldwide. Its production grew at an annual rate of 2.8% from 2015 to 2020, with 168 Mt produced in 2020, and production is expected to grow at a similar rate from 2020 to 2030.

Ethylene can be produced from a wide range of feedstocks<sup>5</sup>, with ethane and liquified petroleum gas (LPG) providing the highest yields. Propane as a feedstock can provide high yields of propylene. The two feedstocks (ethane and propane) have been dominating olefin plant designs in the United States and the Middle East, whereas naphtha is the dominant feedstock in the European Union and Asia. Naphtha as a feedstock is responsible for approximately 43% of global ethylene production, ethane accounts for 35% of it, and other feedstocks for the remainder. In the steam-cracking process, other light olefins and aromatics (BTX) are simultaneously produced with ethylene, and are jointly known as HVC.

### 4.2. Steam cracking

Steam cracking typically refers to producing HVC by breaking down saturated hydrocarbons into smaller olefin hydrocarbons. Technically, a gas separation unit is employed to obtain different types of hydrocarbons, such as ethane, from the natural gas production process: these hydrocarbons are thermally cracked, at up to 1000 °C, in the presence of steam using pyrolysis furnaces. At this stage, two chemical reactions occur: the splitting of C-H bonds and splitting of C-C single bonds. The products obtained in this step depend on the composition of the feedstock, hydrocarbon-to-steam ratio, and cracking temperature. After reaching the cracking temperature, the hot gas mixture is quickly quenched in Transfer Line Exchangers (TLE) to 550-650 °C. The TLEs are then cooled down to 300 °C to avoid any degradation by secondary reactions and to generate high-pressure steam for driving compressors, in particular the raw-gas compressors required to raise the pressure to facilitate the separation of ethylene from other components.

Ethane as a feedstock for steam crackers has the highest carbon yield for ethylene and the lowest process fuel by-product yield. As a result, the use of ethane as feedstock generates the lowest rate of CO<sub>2</sub> emissions. Since the selection of feedstock plays a crucial role in reducing CO<sub>2</sub> emissions for ethylene production, it is of prime importance to maximise the use of ethane in ethylene production so as to reduce process CO<sub>2</sub> emissions. Other HVC petrochemicals, however, need to be produced in different ways, including through catalytic reforming or catalytic cracking in refineries.

### 4.3. Propylene

The maximisation of propylene production by fluid catalytic cracking (FCC) has become the focus of most refineries because propylene is in high demand and there is a supply shortage from modern steam crackers, which now produce relatively less propylene. The flexibility of FCC<sup>6</sup> to adapt to various reaction conditions makes it possible to close the gap between supply and demand. The FCC process can be appropriately modified by the synergistic integration of the catalyst, temperature, reaction-residence time, production of coke, and hydrocarbon partial pressure. The main constraints for maximum propylene yield are limits in having a suitable catalyst, suitable reactor configuration and optimum reaction conditions.

<sup>5</sup> Burdick, Donald L., Leffler, W.L., Petrochemicals in nontechnical language, 4th Ed., PennWell Corporation, Tulsa Oklahoma. [www.pennwellbooks.com](http://www.pennwellbooks.com) 2009045189. ISBN 978-1-59370-216-8

<sup>6</sup> Akah, A., Al-Ghrami, M. Maximizing propylene production via FCC technology. Appl Petrochem Res 5, 377–392 (2015). <https://doi.org/10.1007/s13203-015-0104-3>; <https://www.prnewswire.com/news-releases/2020-global-ethylene-market-and-propylene-industry-research-analysis-by-tbrc-301014325.html>; <https://www.mckinsey.com/industries/chemicals/our-insights/petrochemicals-2020-a-year-of-resilience-and-the-road-to-recovery>; <https://www.hellenicshippingnews.com/pdh-expansion-fuels-chinas-lpg-demand/>

Plants capable of producing both ethylene and propylene may be faced with higher demand for propylene. In that case, 'on-purpose' propylene production may be employed: the plant operating conditions are then adapted to single-product production rather than co-product production with fixed-ratio yields. For such single-product production, propane dehydrogenation is employed, in which propane (along with a small amount of hydrogen to control coking) is fed to a fixed-bed or fluidised-bed reactor at 500-700 °C with a catalyst of platinum activated alumina impregnated with 20% chromium. Despite the presence of hydrogen, some coke will nevertheless form on the catalyst, and the periodic regeneration of the fixed bed, or continuous regeneration of the fluidised bed, is required. The net result in commercial plants is about 85% yield for propylene<sup>7</sup>.

#### 4.4. Options for decarbonisation

Demand for Ethylene / HVC has been strongly increasing in recent years and is expected to continue doing so in the future. Even Net Zero by 2050 Emissions Scenarios foresee regional capacity expansion for crackers, predominantly in North America, the Middle East and the Asia Pacific region. This context highlights the need for rapid measures to reduce energy consumption and the intensity of CO<sub>2</sub> emissions in the production of ethylene and propylene. Possible options include the following.

- Increase the yield of feedstock conversion to ethylene / HVC by improving the design of reaction coils and other process equipment and / or maximising the use of light hydrocarbon feedstocks (ethane and liquified petroleum gas (LPG)).
- Maximise the use of ethane or LPG in steam crackers and increase the production of propylene and aromatics in refineries.
- Replace fossil-fuel heating with low-carbon electricity to produce heat in steam-cracker furnaces.
- Produce specific HVCs with feedstocks of similar structure to improve product yields, such as, for example, propane dehydrogenation to produce propylene.
- Apply carbon capture and storage (CCS) to the exhaust gases from pyrolysis furnaces to eliminate CO<sub>2</sub> emissions when ethylene is being produced.
- Employ green hydrogen and captured CO<sub>2</sub>, rather than coal, for the production of methanol in the MTO (Methanol to Olefins) processes commercially implemented in China, an approach capable of achieving significant decarbonisation.

<sup>7</sup>

Burdick, Donald L., Leffler, W.L., Petrochemicals in nontechnical language, 4th Ed., PennWell Corporation, Tulsa Oklahoma. [www.pennwellbooks.com](http://www.pennwellbooks.com) 2009045189. ISBN 978-1-59370-216-8

## 5. Ammonia

Ammonia production accounts for about 1.0% of global annual CO<sub>2</sub> emissions, which is more than any other industrial chemical.

### 5.1. Manufacturing process and current use

Ammonia is manufactured in all regions of the world<sup>8</sup>. With around 30% of the global production, China is by far the largest ammonia manufacturer. The United States, Europe, India, Russia and the Middle East follow with about 8% each, and other nations contribute in the lower single-digit percentage range. Apart from abundant globally-available nitrogen, manufacturing ammonia requires hydrogen. It is theoretically necessary to supply 177 kg of H<sub>2</sub> and 823 kg of N<sub>2</sub> to produce 1 tonne of ammonia. Natural gas is responsible for 70% of the energy that global ammonia production requires. Indeed, natural gas is the major feedstock for hydrogen generation, followed by coal with 26%, while oil and electricity account for the remaining 4%<sup>9</sup>. The production of ammonia thus generates CO<sub>2</sub> emissions: of 1.6 tCO<sub>2</sub>/tNH<sub>3</sub> when natural gas is employed for hydrogen generation, 3.0 tCO<sub>2</sub>/tNH<sub>3</sub> when fuel oil is employed, and 3.8 tCO<sub>2</sub>/tNH<sub>3</sub> when coal is. In Europe, the ammonia industry uses 50% of all industrially produced hydrogen. More than 75% of the annual ammonia production is used for fertilisers, either directly or as a precursor for nitrogenous fertiliser products, while the remaining ammonia is used as a refrigerant as well as for manufacturing explosives, textile fibres, pharmaceuticals and electronic materials.

Almost all ammonia is exclusively produced by the same route, the Haber-Bosch process, in which hydrogen reacts with nitrogen, taken from air, at high temperature and pressure, over an iron (Fe) or ruthenium (Ru) catalyst. Although the reaction between nitrogen and hydrogen in the Haber-Bosch process is an exothermic one, the energy released by the reaction is largely insufficient to cover energy requirements. In terms of net overall energy balance, the process is energy-consuming: hydrogen production is very energy intensive, and to that first energy requirement must be added the energy required for nitrogen separation, process heating and process compression. Indeed, the overall energy balance of the process is such that about 60% of the total energy requirement relates to hydrogen production<sup>10</sup>.

### 5.2. Use and projection for future use

For certain regions such as Europe, a slight decrease in nitrogen-based fertiliser application is forecast for 2030; however, this is compensated by predicted annual growth in other regions of the world, thereby resulting in overall single-digit percentage growth worldwide.

Ammonia is in itself toxic to humans, and ammonia derivatives such as urea, ammonium nitrate and ammonium sulphate employed as nitrogenous fertilisers can pose health risks and threaten ecosystems. Although ammonia is not a greenhouse gas per se, soil bacteria can convert nitrogenous compounds in the soil to nitrous oxide, a potent greenhouse gas, and nitrogen compounds (in particular, nitrates) contribute to water eutrophication. Nitrogen fixation from the global use of nitrogenous fertilisers is already equivalent to natural nitrogen fixation by soil bacteria. However, an increase in nitrogen efficiency in agriculture, through better farming practices, has the potential to reduce nitrogenous fertiliser use by 10% to 20% with respect to current practice. Still, the global quantities of ammonia produced will remain very high for the foreseeable future.

In addition to its role in agriculture, ammonia has the potential of being an attractive energy (hydrogen) storage medium, due to the existing worldwide transport network for liquid ammonia. As a low-carbon fuel, ammonia could partially or totally replace a number of conventional fuels. There is thus a significant advantage to using ammonia in terms of transport cost compared to liquid hydrogen, and the economics do improve if ammonia is used as a direct fuel.

<sup>8</sup> Global ammonia production by country 2020 | Statista Global ammonia production by country 2020 | Statista

<sup>9</sup> <https://cen.acs.org/environment/green-chemistry/Industrial-ammonia-production-emits-CO2/97/i24>

<sup>10</sup> Ammonia Uses and Benefits | Chemical Safety Facts

These potential advantages may justify the conversion from the direct use of low-carbon hydrogen to green ammonia. In the ideal case, the combustion process of ammonia should generate only nitrogen and water<sup>11</sup>, but in practice the combustion gases often contain variable quantities of nitrogen oxides and unburnt ammonia. Considerable development effort is therefore currently being deployed to use ammonia in internal combustion engines (ICE)<sup>12</sup>, for example for marine engines. Two marine engine manufacturers are currently retrofitting diesel engines to burn ammonia. Indeed, green ammonia holds the potential for a 95% GHG reduction in maritime transport, depending on the full development of direct combustion engines.

The energy density of liquid ammonia is 15.6 MJ/l (4.3 kWh/l), which is 70% more than liquid hydrogen and about 40% of today's carbon-based liquid fuels. The energy density of ammonia is also about 10 times higher than that of battery storage, which makes it a good candidate for energy storage and use in solid oxide fuel cells (SOFCs). For use as storage gas for low-carbon energy, ammonia would best be produced close to the energy production sites and in smaller installations than those available today, provided similar manufacturing efficiency is attainable in smaller installations.

### 5.3. Reducing carbon greenhouse emissions

There are two main approaches to reducing GHG emissions caused by ammonia production and use. One is improving its manufacturing process; the other, improving efficiency in the use of ammonia in agriculture.

Regarding the manufacturing process, the main focus for GHG reduction is on using low-carbon hydrogen (See chapter *"To set the scene, annex 2"*). A modern, optimised and highly efficient methane-fed Haber-Bosch process emits about 2 tCO<sub>2</sub>/tNH<sub>3</sub>. Switching the hydrogen production method from methane to electrolysis of water reduces CO<sub>2</sub> emissions by about 75%, but the manufacturing process competes with many other uses for low-carbon hydrogen.

Another approach involves downscaling and improving the catalytic Haber-Bosch reaction, which would allow smaller plants closer to low-carbon energy sources to be constructed, with ammonia being employed as a storage fuel. Such technology is currently being tested at a Technology Readiness Level (TRL) of 4. The Haber-Bosch synthesis (HBS) uses high pressure and high temperature combined with a specific catalyst. Over the last century, the process has been continuously optimised, progressively halving the minimum energy requirement per tonne. Most of this progress was achieved prior to 1990 and further improvements have been limited since then. However, approaches for smaller installations are being developed<sup>13</sup>.

The second important path to reducing the GHG footprint is to improve nitrogen-use efficiency in agriculture, which would have the additional benefit of reducing soil and water pollution. In Europe, nitrogen uptake in plants improved from 50% to 59% during the period from 1990 to 2004. The current goal is to increase nitrogen-use efficiency globally through better farming practices. In digital and precision farming, the individual field is monitored and fertilised according to crop needs.

<sup>11</sup> Ammonia: zero-carbon fertiliser, fuel and energy store Issued: February 2020 DES5711, ISBN: 978-1-78252-448-9 © The Royal Society

<sup>12</sup> Shigeru Murali: Development of Technologies to utilize Green Ammonia in Energy Market; SIP Energy Carriers Cabinet, Government of Japan (2018); Giddey et al, Ammonia as a Renewable Energy Transportation Media, ACS Sustainable Chemistry & Engineering, 09/27/201721; <https://www.ammoniaenergy.org/articles/round-trip-efficiency-of-ammonia-as-a-renewable-energy-transportation-media/>

<sup>13</sup> <https://www.sciencedirect.com/science/article/pii/S0360319921012660>; <https://onlinelibrary.wiley.com/doi/full/10.1002/aesr.202000043>

## 6. Methanol

Methanol is widely used in the chemical industry for producing other chemicals such as formaldehyde, plastics and acetic acid. Globally, approximately 110 Mt of methanol are produced annually, almost exclusively from fossil fuels (35% grey methanol from natural gas and 65% brown methanol from coal). In 2019, only 0.2% of methanol was green methanol produced from low-carbon sources. The current life-cycle emissions of methanol are estimated to be about 0.3 Gt of CO<sub>2</sub> per year, and account for 10% of all the emissions of the chemical sector<sup>16</sup>. Over the past decade, the production of methanol has nearly doubled, largely propelled by growth in China, which in 2015 accounted for over half of global production<sup>14</sup>. According to current trends, the global production of methanol could reach 550 Mt per year by 2050<sup>15</sup>.

The largest increase in demand for methanol is for the Methanol to Olefins (MTO) process, in which methanol can be converted into olefins, such as ethylene and propylene. The olefins may then be used to make polyolefins, which are used to produce various plastic materials. To successfully apply the MTO process, acidic zeolite catalysts are required<sup>16</sup>. MTO production is estimated to increase by 7% annually<sup>17</sup>.

### 6.1. Reducing carbon greenhouse emissions

Green methanol, which is called e-methanol if it is produced using low-carbon electricity, is obtained via the gasification of biomass or municipal solid waste. The production of such bio-methanol or of e-methanol decreases the carbon footprint and harmful emissions (SO<sub>x</sub>, NO<sub>x</sub>, particulate matter) in comparison to the production of grey or more importantly brown methanol. While the processes on which methanol production are based are relatively mature, there is only a handful of commercial bio-methanol plants. The average energy efficiency of these plants ranges between 53% and 62%<sup>18</sup>.

## 7. Future scenarios

The chemical process industries (CPI) take raw materials from the petroleum industry and minerals extraction, as well as natural products, to produce chemicals and materials used in other industries, through a web of unit processes. Water is another input, as well as the provision of process media and cooling.

Much of the input is incorporated into products, and, without refinery products, many chemicals would require carbon inputs from biomass or CO<sub>2</sub> captured from the atmosphere.

The industry employs 15 million people. Indirect and induced impacts included, it supports 120 million people and 7% of global GDP. Annual capital spending is USD 210 billion. The centre of gravity of the global industry is in Asia. Given its size and the incorporation of chemicals into products from virtually all industrial sectors, challenges for sustainability in the chemical process industries are numerous and wide-ranging<sup>19</sup>.

### 7.1. Extrinsic factors and challenges

The industry has been growing over the last two centuries to meet a wide range of needs alongside economic and demographic development, and CPI production is expected to continue increasing. It is in the context of this continued growth in demand that the transition to net zero emissions will require faster and more dramatic changes over the next thirty years.

Among the challenges to address, changes are to be expected in the upstream availability of raw materials and energy due, for example, to transformations in the fossil-fuel industry or in sustainably-produced vegetable oils. Moreover, the industry will face changes in downstream demand: recycling will play a prominent role and some uses may be restricted because of unavoidable impacts or losses into the environment.

Interactions within the global economy and competition for resources, such as land, are too complex to un-

<sup>14</sup> <https://www.methanol.org/wp-content/uploads/2016/07/IHS-ChemicalBulletin-Issue3-Alvarado-Jun16.pdf>

<sup>15</sup> [https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA\\_Innovation\\_Renewable\\_Methanol\\_2021.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf)

<sup>16</sup> <http://www.cchem.berkeley.edu/molim/teaching/fall2009/mto/background.html>

<sup>17</sup> <https://www.methanol.org/wp-content/uploads/2016/07/IHS-ChemicalBulletin-Issue3-Alvarado-Jun16.pdf>

<sup>18</sup> [https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA\\_Innovation\\_Renewable\\_Methanol\\_2021.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf)

<sup>19</sup> The Global Chemical Industry: Catalyzing Growth and Addressing Our World's Sustainability Challenges, Oxford Economics, 2019; Planetary metrics for the absolute environmental sustainability assessment of chemicals, Tulus et al, Green Chemistry, Vol 23, Number 24, Dec 2021, 9707-10172; The net-zero transition: What it would cost, what it could bring, McKinsey & Co, Jan 2022

ravel without global systems models – taking into account the socio-demographic, technological, environmental and economic factors. How costs along the chemicals supply chains will interact with other factors cannot be discussed without such models. Conversely, scenario analyses may identify potentially viable pathways and branching points.

## 7.2. Increased process energy requirements for electrification and CCUS

As indicated in the previous sections, the primary paths to substantially reducing GHG emissions and overall carbon footprint in the chemicals sector will call upon two fundamental mechanisms:

- a. electrification, both as a substitute for process heating in the production of ethylene and propylene and to produce low-carbon hydrogen by electrolysis for ammonia and other chemical building blocks such as methanol;
- b. carbon capture, utilisation and storage (CCUS), allowing production facilities unable to convert to electrification to avoid CO<sub>2</sub> emissions from outlet process streams (including those related to the use of fossil carbon for heating).

In either cases, electrification or CCUS, the total energy requirement per unit of chemicals production will increase in comparison to current practice, and such increasing energy requirement will be multiplied by the increasing demand stemming from economic and demographic development.

It is therefore imperative that the future energy requirements of the industry (even for hydrogen production and CCUS) be satisfied with energy sourcing through nuclear power or renewables. Therefore, the current employment of coal and natural gas as energy sources in many areas of the world constitutes a major challenge.

Among others, one possible avenue may be explored in this connection: the potential of bio-sourcing as a supply for a portion of the process energy required for the CPI (in addition to the bio-sourcing of feedstocks).

## 7.3. Bio-sourcing the process energy for the CPI: perspectives and limits

Ethanol produced from various bio-based sources has recently gained considerable attention owing to its potential to decrease CO<sub>2</sub> net emissions while also reducing the global reliance on fossil fuels<sup>20</sup>. Global ethanol production increased from 24 Mtoe in 2007 to 53 Mtoe in 2019, only to fall to 48 Mtoe in 2020 due to the Covid-19 pandemic<sup>21</sup>.

With a production of 1 190 200 barrels daily, the United States of America is the largest biofuel producer in the world, with a 45% share in 2018. Brazil ranks second with a 2018 output of 693 200 barrels/day, or 27% of global production. While the vast majority of US ethanol is produced from corn and maize, sugar cane has been used as the primary feedstock for ethanol production in Brazil.

Other significant producers of ethanol include the European Union, China, and Canada at 5%, 3%, and 2% of total worldwide production, respectively. Germany is Europe's largest producer with 75 800 barrels produced per day, a 3% global market share, in 2018, and is closely followed by Argentina with 70 600 barrels per day and China with 68 000 barrels per day<sup>22</sup>.

According to the IEA<sup>23</sup>, the global process energy consumption for primary chemicals production in 2020 is estimated at 9.3 EJ (exajoules), equivalent to 2584 TWh. Global bioenergy power generation increased by 8% in 2020 to reach a value of 718 TWh, but most of such bioenergy power is already employed in other energy-intensive sectors such as transport. Given this context, as well as the magnitude of the energy requirements involved, it appears unlikely that global bio-ethanol production would cover more than a small proportion, in the order of a few percent, of the required energy sourcing of the CPI in the next 10 to 20 years. Bioenergy needs to pass stringent Life Cycle Assessment (LCA) tests. The best use of high grade land is for food production and low grade land for woody biomass.

<sup>20</sup> Tuan-Dung Hoang, Nhuan Nghiem(2021), Recent Developments and Current Status of Commercial Production of Fuel Ethanol, Fermentation 2021, 7(4), 314

<sup>21</sup> Global Ethanol Production by Country or Region. Available online: <https://afdc.energy.gov/data/10331/> (accessed on 10.02.2022).

<sup>22</sup> <https://www.nsenenergybusiness.com/features/top-biofuel-production-countries/>

<sup>23</sup> Process energy for primary chemical production in the Net Zero Scenario, 2015-2030, IEA, Paris, <https://www.iea.org/data-and-statistics/charts/process-energy-for-primary-chemical-production-in-the-net-zero-scenario-2015-2030>

#### 7.4. Charting individual paths

Chemicals are significantly traded across the world. Such global trade accounts for 45% of all chemicals GDP. In the absence of customised systems models at the country and regional levels, and more general global models, it is most difficult to know how each country should navigate its path between reducing its environmental footprint and improving the well-being of its citizens. Countries with more resources, which may be further ahead, need to address their own challenges and collaborate more widely, including with technology transfer between countries where the production of new chemicals is required.

Moreover, some drivers of GHG emission reduction push against each other. Reductions in chemical industry green-house gas emissions in the EU, for example, have largely stemmed from eliminating nitrous oxide leakage from such processes such as for example nitric acid, adipic acid, etc. There are also emissions embedded in inputs. For example, the production of natural gas involves avoidable fugitive methane emissions in many regions. Liquefied natural gas (LNG), likewise, uses energy from fossil fuels in its liquefaction. Switching to more sustainable sources and reducing use will both be important.

Land and sustainable biomass are limited resources, and increasingly precious ones. Although structural inefficiencies and misplaced incentives will continue, there will be pressures to use land in a more effective manner. This will interact with the chemical industry in multiple ways, for example to reduce food wastage by refrigeration. If secure and affordable geological CO<sub>2</sub> storage is abundant, then spare land is best used to produce woody biomass to create negative emissions credits through bioenergy with carbon capture and storage (CCS). If it is scarce, then it will be best used for liquid biofuels and chemical feedstocks.

#### 7.5. Technologies, assets and skills

The industry has a large stock of sophisticated and high-capital-cost assets. Many of these are relatively new, and built to supply the expanding demand in rapidly developing economies. Reshaping this stock of assets and growing it will be challenging and require all the skills of the current workforce, supported by appropriate mechanisms from governments. The pace and cost of asset formation will be a constraint on progress, determining which technologies are available for scale up in time.

It is therefore essential to accelerate the development of the required emerging technologies based on current knowledge and concepts: a large market is waiting for commercially-proven technologies to be available for the decarbonisation of the industry and deployed for large-scale use as soon as possible. To accelerate these developments, it is necessary to reduce the risk involved in capital investment. In this goal, targeted subsidies will have an important role to play in addition to other incentive measures. Without proven commercial technologies, however, it will not be possible to commit the billions of dollars of private capital that should be rapidly assigned to building the new facilities required to have major impact on GHG-emission reduction in the forthcoming decades. All new technologies will need rigorous LCA.

Although breakthrough innovation will be welcome as well, most of it will be too late. Efficiency is a temporary measure to quickly reduce emissions; efficiency in downstream assets reduces investment in upstream assets, including energy supplies.

In addition to investing resources into a new set of products that involve more recycling and different inputs and processes, the chemical industry will be more broadly called upon to offer its skills and technologies. It is unlikely that all fossil-hydrocarbon uses be replaced with electricity; therefore, low-carbon hydrogen will be required at scale. The global marine industry sees ammonia as a potentially more usable fuel than hydrogen. Methanol is likely to grow faster as a carrier for energy and carbon.

In many scenarios, the direct recapture of CO<sub>2</sub> from the atmosphere at a scale of over 1 Gte per year will be required by 2050. How much of this will be injected into long-term and secure geological storage sites is very unclear. A large part may perhaps be converted to fuels and chemical feedstock, preserving precious storage to only offset unavoidable emissions (and repair the damage caused by historic excess emissions). Given the scale of CO<sub>2</sub> recapture from the air and of hydrogen production, as the starting point for fuels and feedstocks, significant investments will be required, including in additional electricity generation.

## 8. Key Messages / Recommendations

A large number of effective and varied approaches may be envisioned to substantially reduce the carbon footprint of the processes employed in the chemicals sector. The non-exhaustive list of key messages and recommendations below draws upon a realistic assessment of the development of the chemicals sector over the next 10 to 20 years and focuses on the most promising options based on available (or likely to be available) technology over the next 20 years.

In addition to its production processes, the chemical industry, from its raw materials to its final products, has many connections with the entire economy; whole-systems Life Cycle Analysis (LCA) is thus required to the process of understanding such a situation. The efficient use of energy and materials at the systems level is an important consideration, since the use of chemical products may lead to the accumulation of waste in the air and ground water, oceans, soil and living organisms with a range of potential negative effects. While these wider issues are acknowledged and need to be addressed, the scope of the present chapter was to target the more limited issues of energy use within the chemical process industries and CO<sub>2</sub> emissions directly related to the use of energy in the chemical production processes themselves.

### *Key messages*

#### 8.1. **Major high-tonnage chemical production will not disappear in the next 10 to 20 years**

Global population growth and economic development will lead to increased demand for high-value chemicals (ethylene, propylene, benzene, toluene and xylenes), as well as ammonia and methanol. As a result, it is imperative to reduce the emission of greenhouse gases in the industrial production of these products by determined action in the transformation of the chemical process industries (CPI).

#### 8.2. **The decarbonisation of the chemical process industries (CPI) can begin immediately through proper deployment of currently available technologies and improved feedstock efficiency**

It is not necessary to wait for new developments, and it is urgent to deploy immediately those technological approaches that are the most promising and readily available. Such approaches include the reuse, reduction and recycling of carbon-based materials (plastics in particular), reduction in nitrogenous fertilisers, electrification of process heating, low-carbon hydrogen production and improvement in feedstock efficiency.

#### 8.3. **Carbon capture, utilisation and storage will be required**

Since it will not be possible to completely transform all processes and production sites in the next 10 to 20 years, the use of carbon capture, utilisation and storage technology (CCUS) for exhaust gases from production processes will be required for the chemical process industries to attain the greenhouse gas emission targets.

### *Recommendations*

#### 8.4. **Accelerate the reuse, reduction and recycling of carbon-based materials (in particular plastics)**

The replacement of single-use plastic materials, in particular for packaging, can be an effective mechanism to limit the production volumes of plastics, such as polyethylene and polypropylene, and thereby reduce the greenhouse gas emissions associated with their production. Waste recycling may offer the opportunity to reincorporate already produced materials into new products, thereby reducing the total energy use (and associated greenhouse gas emissions) required for production.

#### 8.5. **Reduce the use of nitrogenous fertilisers through improved agricultural practices**

The production of ammonia, among all of the major high-tonnage chemicals examined in the present report, is the process that has the highest specific energy requirement. As a result, and without any changes to the ammonia process itself, a significant contribution to reducing greenhouse gas emission may be achieved through a drop in the volumes of nitrogenous fertilisers required in agricultural production.

**8.6. Electrification of process heating with low-carbon electricity**

The production of the high-tonnage chemicals examined in the present report is particularly energy intensive. Replacing the coal and natural gas currently required for process heating, in particular in steam cracking, by low-carbon (or nuclear) electricity is therefore an indispensable transition step that can be implemented with existing available technology.

**8.7. Large-scale development of low-carbon hydrogen production (in particular for ammonia synthesis)**

To reduce the carbon footprint resulting from the manufacture of ammonia, it is of utmost importance to transition from the current hydrogen production processes to low-carbon hydrogen production approaches. Two options are possible: (1) hydrogen produced by the electrolysis of water (with low-carbon or nuclear electricity); or (2) hydrogen produced by the reforming of natural gas (as it is practiced today) but with carbon capture and storage (CCS) of the CO<sub>2</sub> emitted during the transformation.

**8.8. Increase the use of ethane for ethylene production and replace coal with natural gas for methanol production**

Replacing naphtha and other heavy petroleum fractions with ethane in the steam-cracking process to produce ethylene generates higher selectivity for ethylene and thereby constitutes a major step in the necessary increase in efficiency of ethylene production worldwide. The transition from coal to natural gas for the production of methanol also constitutes an important advance. Although such improvements in feedstock efficiency will not totally eliminate greenhouse gas emissions from the production of ethylene and methanol, they will clearly and rapidly contribute to their significant reduction in the short to medium term.

## List of abbreviations and acronyms

---

<b>BTX</b>	Benzene, Toluene and Xylenes
<b>CCS</b>	Carbon Capture and Storage
<b>CCUS</b>	Carbon Capture, Utilisation and Storage
<b>CPI</b>	Chemical Process Industries
<b>FCC</b>	Fluid Catalytic Cracking
<b>GDP</b>	Gross Domestic Product
<b>GHG</b>	Greenhouse Gas
<b>HBS</b>	Haber-Bosch Synthesis
<b>HVC</b>	High Value Chemicals
<b>ICE</b>	Internal Combustion Engine
<b>IEA</b>	the International Energy Agency
<b>LNG</b>	Liquified Natural Gas
<b>LPG</b>	Liquified Petroleum Gas
<b>MTBE</b>	Methyl tert-Butyl Ether
<b>MTO</b>	Methanol to Olefins
<b>SOFC</b>	Solid Oxide Fuel Cell
<b>TLE</b>	Transfer Line Exchanger
<b>TRL</b>	Technology Readiness Level

---

## CHAPTER 5. THE CEMENT INDUSTRY

### Members of the Working Group

**Cai Rui**, China (Co-chair)

**Chakraborty Sudhangsu Shakhar**, India

**Duic Neven**, Croatia (Co-chair)

**Evans Robert**, Canada

**Giovambattista Alberto**, Argentina

**Kearsley Elisabeth**, South Africa

**Perry Brian**, South Africa

## Table of Contents

---

<b>Executive Summary</b> .....	172
<b>1. Introduction</b> .....	173
<b>2. Current situation</b> .....	177
2.1. The cement manufacturing process in brief .....	177
2.1.1. Exploitation of raw materials .....	177
2.1.2. Mixing of raw materials and clinkerization .....	177
2.1.3. Grinding and distribution .....	177
2.2. Worldwide production .....	179
2.3. Energy consumption of the cement industry .....	181
2.3.1. Energy source in the cement industry .....	181
2.3.2. Energy transition trend in different countries .....	182
2.4. CO <sub>2</sub> Emission in the cement production .....	182
2.4.1. CO <sub>2</sub> emission intensity of the cement production .....	182
2.4.2. CO <sub>2</sub> emission intensity of clinker for different countries .....	183
<b>3. Technologies for decarbonisation</b> .....	184
3.1. Energy efficiency improvements .....	184
3.2. Alternative raw materials .....	189
3.3. Alternative fuels: waste, biomass, green hydrogen and others .....	191
3.4. Low carbon cement .....	195
3.5. Carbon capture, utilisation and storage (CCUS) .....	196
<b>4. Decarbonisation policy</b> .....	201
4.1. Existing carbon reduction policies .....	201
4.2. Policy recommendations .....	204
4.2.1. Supportive policies for carbon reduction technologies .....	204
4.2.2. Carbon market mechanisms .....	206
4.2.3. Environmental Protection Policies .....	206
<b>5. Pathway to net-zero CO<sub>2</sub> emission</b> .....	207
5.1. Carbon reduction potential of decarbonisation technologies .....	207
5.1.1. Energy efficiency improvement .....	207
5.1.2. Alternative raw material .....	207
5.1.3. Alternative fuel .....	207
5.1.4. Low carbon cement .....	207
5.1.5. CCUS .....	207
5.2. Pathway to net-zero CO <sub>2</sub> emission .....	208

<b>6.</b>	<b>Case studies</b>	208
6.1.	Dalmia cement of India	208
6.2.	Brevik carbon capture and storage project	209
6.3.	Low Emissions Intensity Lime And Cement (LEILAC) projects	210
6.4.	LafargeHolcim cement plant	211
6.5.	Huaxin's cement kiln domestic waste cooperative disposal technology	211
<b>7.</b>	<b>Key messages and recommendations</b>	212
7.1.	Clear, stable and holistic public policies and incentive regulations to encourage carbon emission reduction of the cement industry	213
7.2.	Deploying low-carbon available technology and improving research and development	213
7.3.	The CCUS will certainly be required to reach the low-carbon objectives	213
7.4.	Developing and updating benchmarks and standards	213
7.5.	Promoting close cooperation between cement and other industries and achieve overall carbon emission reduction	213
	<b>List of abbreviations and acronyms</b>	214

## Executive Summary

---

The scope of this chapter is cement production. It analyses the current situation of the cement industry and the progress in low carbon cement production technologies. It also puts forward policy recommendations and technical paths to achieve further low-carbon developments in this industry in the future.

It first provides an outline of the global cement production, market situation, and carbon emission levels, and investigates the relationships between cement production, GDP and the share of carbon emissions in various countries. In 2020, 4.3 billion tonnes of cement were produced globally and the cement industry alone accounted for about 7% of global carbon emissions, e.g., around 2.5 billion tonnes CO<sub>2</sub>. In the future, cement demand is expected to grow further as demand from developing countries expands in areas such as infrastructure construction and real estate, which shows the importance to reduce cement industry emissions.

The cement industry is a typical resource-based, energy-intensive, and emission-based industry: the usual materials and chemical reactions to obtain cement are producing themselves CO<sub>2</sub>. The main fuel type is fossil energy, which accounts for more than 90% of the total consumption, and the rest is biomass and waste.

Cement producers are increasingly applying currently feasible methods to reduce carbon emissions. These include low-temperature waste heat power generation technology and the adoption of alternative raw materials as well as – to some extent – fuel technologies that are still in the demonstration stage, such as calcium carbide slag, oil shale, biomass, green hydrogen, and waste. These initiatives will foster the development of cement with a low-carbon footprint and a low-carbon development path in conjunction with the progress in carbon capture utilisation and storage (CCUS) technologies which will certainly be required to reach the emissions reduction objectives.

In addition to continuously developing and promoting the application of low-carbon production technologies, many countries and regions are implementing effective incentive policies and regulations, encouraging and guiding the development and application of low-carbon technologies, carbon market mechanisms, and environmental protection.

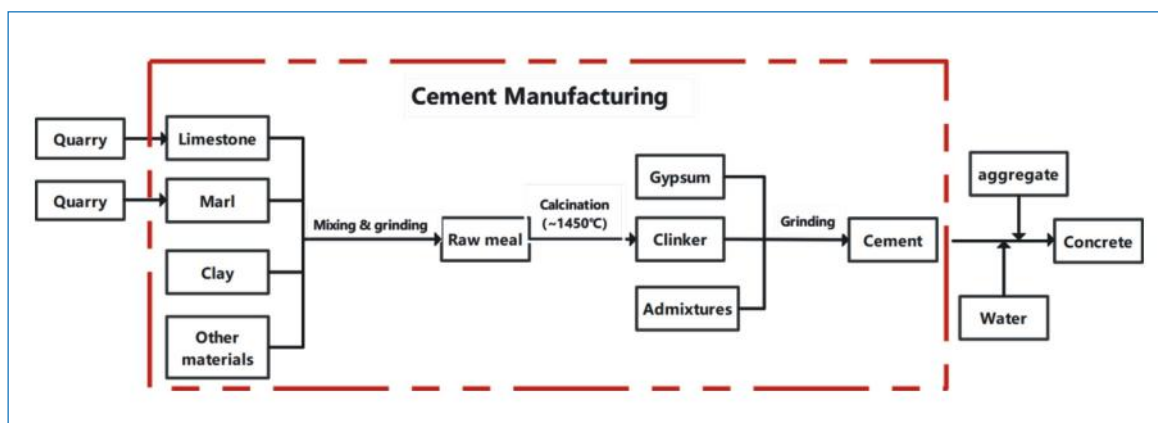
Finally, combining all the inputs of this study, a pathway to achieving a carbon-neutral cement industry can be projected assuming that stable and holistic public policies are implemented. These must promote and incentivise research and development in low carbon technologies, emphasise the importance of CCUS for the cement industry, and facilitate the integration with other industries, such as steel or thermal power generation. Enhancing the development of a low-carbon cement industry, depends to a large extent on international cooperation in research and application of low-carbon technologies. Such cooperation should accelerate the complete reformulation of cement industry standards. Meanwhile, research into low-carbon technologies for both upstream and downstream cement production processes is needed.

## 1. Introduction

Cement is an important building material in the development of a national economy. How to reduce carbon emissions from cement production, and yet ensure such production continues to satisfy demand, is the biggest challenge for the cement industry.

Based on the current situation and challenges of the global cement industry, this chapter looks into the means of reducing its carbon emissions and makes policy recommendations that may eventually open carbon reduction pathways and provide a reference for its sustainable development.

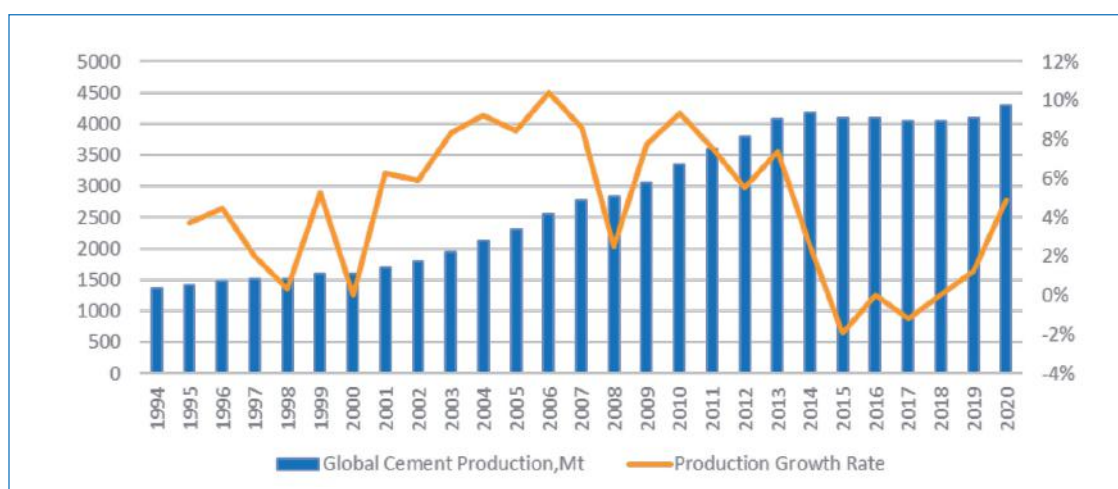
This chapter focuses on the reduction of CO<sub>2</sub> emission in cement manufacturing (as indicated *Fig. 5.1.*), as this process produces most of the industry's CO<sub>2</sub> emissions. Neither quarrying nor the production of concrete shall be discussed.



*Fig. 5.1.* The research scope of this report is cement manufacturing

From 1994 to 2012, global cement production grew at a strong rate as demand from industries expanded, in particular for the global industrialisation process and in infrastructure construction. Global cement production has been around 4 billion tonnes since 2013 (4.3 billion tons in 2020) as shown in *Fig. 5.2.*

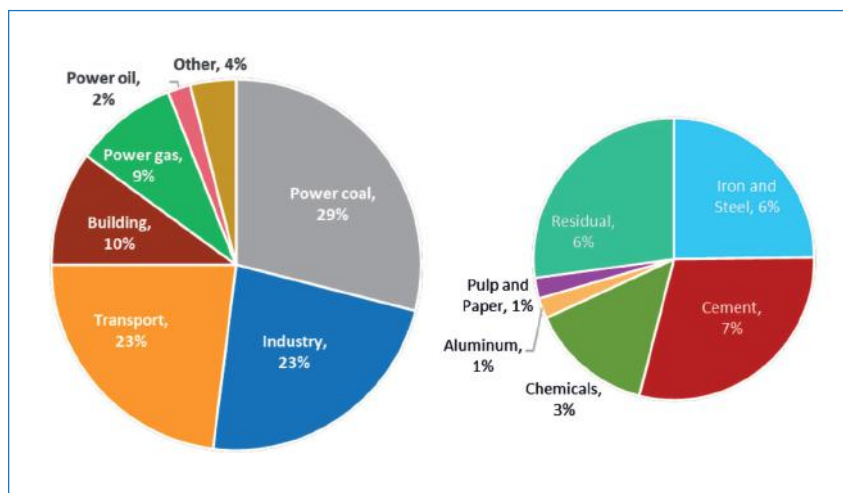
The global cement market size was valued at USD 326.81 billion in 2021. This market is projected to grow from USD 340.61 billion in 2022 to USD 481.73 billion by 2029, exhibiting a “Compound Annual Growth Rate (CAGR)” of 8.1%.



*Fig. 5.2.* Global cement production and production growth rate<sup>1</sup>

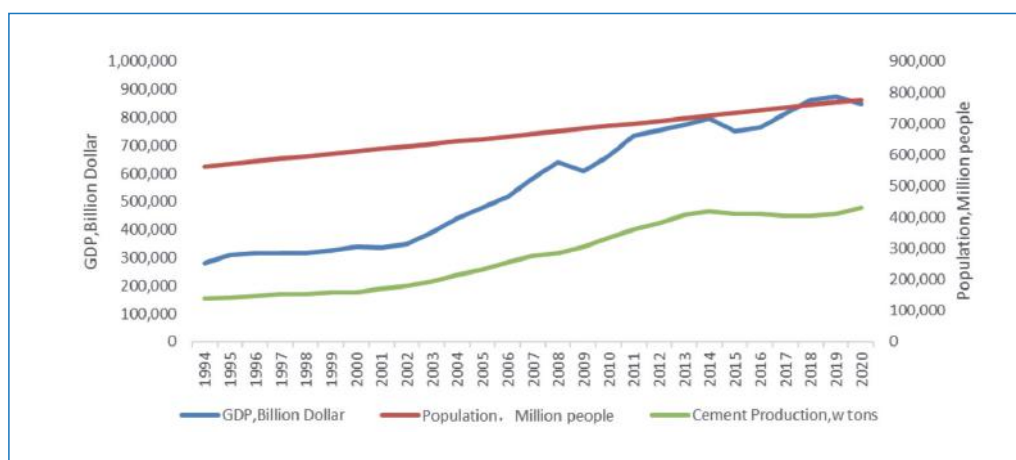
<sup>1</sup> U.S. Geological Survey, Cement Statistics and Information (<https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information>)

The three sectors of the world economy with the highest carbon emissions are coal-based power generation, the industrial sector and transportation, as shown in *Fig. 5.3.*, with the industrial sector accounting for about 23% of the total carbon emissions. The cement industry alone accounts for about 7% of global carbon emissions, i.e. around 2.54 billion tonnes CO<sub>2</sub> in 2020<sup>2</sup>.



*Fig. 5.3.* Global energy-related CO<sub>2</sub> emissions by sector<sup>3</sup>

Demand for cement is related to economic development (of which GDP is one indicator), fixed asset investment, housings investment, population, etc. *Fig. 5.4.* shows cement production has a positive linear relationship with GDP and population growth. According to the trends, such amount will remain high in the near future. It is thus essential to decarbonise the cement industry.



*Fig. 5.4.* Principal characteristics of the global cement industry<sup>4, 5, 6</sup>

As countries are at different stages of economic development, there is a wide gap in the demand for cement. For developing countries such as China, India and Africa, economic and social development is in a rapid growth trend, demand for cement is still high and will keep growing in the future in order to keep pace with the increasing urbanisation and meet the demand for infrastructure, as shown in *Fig. 5.5.* and *Fig. 5.6.*

<sup>2</sup> (2021), Cement tracking report (<https://www.iea.org/reports/cement>)

<sup>3</sup> IEA(2021), Global energy-related CO<sub>2</sub> emissions by sector  
left: <https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-by-sector>, right: <https://www.iea.org/reports/industry>

<sup>4</sup> World Bank, Global population

<sup>5</sup> U.S. Geological Survey, Cement Statistics and Information (<https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information>)

<sup>6</sup> International Monetary Fund, Global GDP

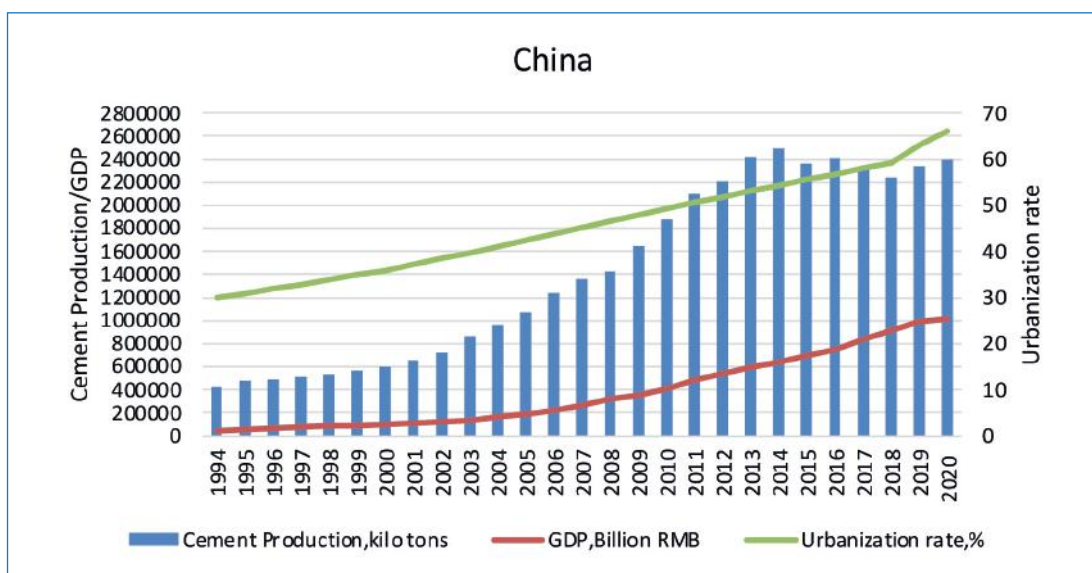


Fig. 5.5. Principal characteristics of the cement industry in China<sup>7,8</sup>

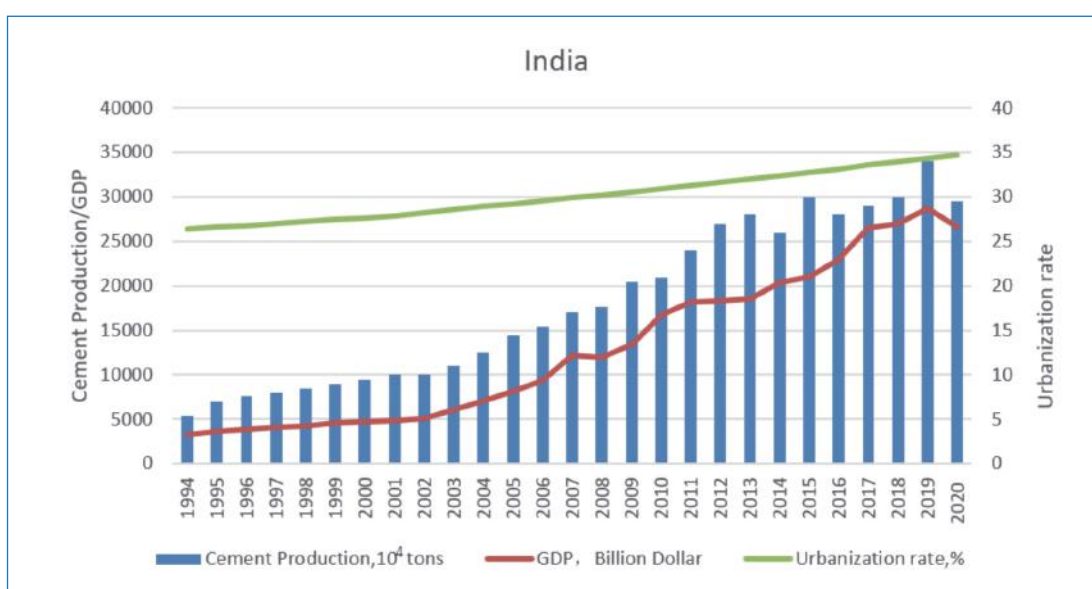


Fig. 5.6. Principal characteristics of the cement industry in India<sup>9,10</sup>

For developed countries with a high level of economic development, such as Europe and the United States of America, demand for cement is growing more slowly as shown in Fig. 5.7. and Fig. 5.8..

<sup>7</sup> National Bureau of Statistics of China, China population

<sup>8</sup> U.S. Geological Survey, Cement Statistics and Information (<https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information>)

<sup>9</sup> Indian Bureau of Statistics, GDP & population statistics

<sup>10</sup> U.S. Geological Survey, Cement Statistics and Information (<https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information>)

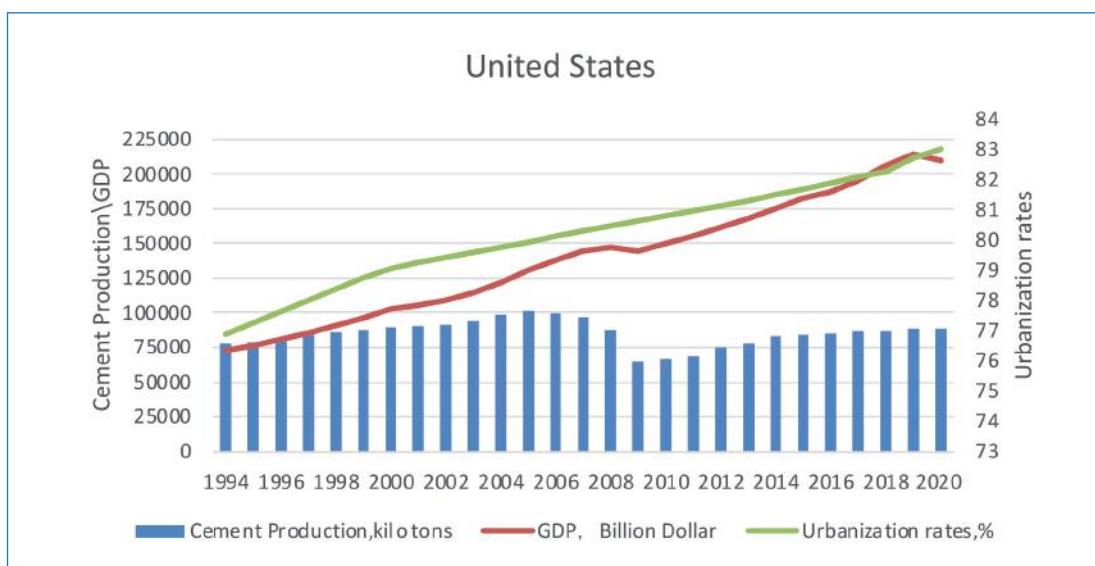


Fig. 5.7. Principal characteristics of the cement industry in United States<sup>11, 12</sup>

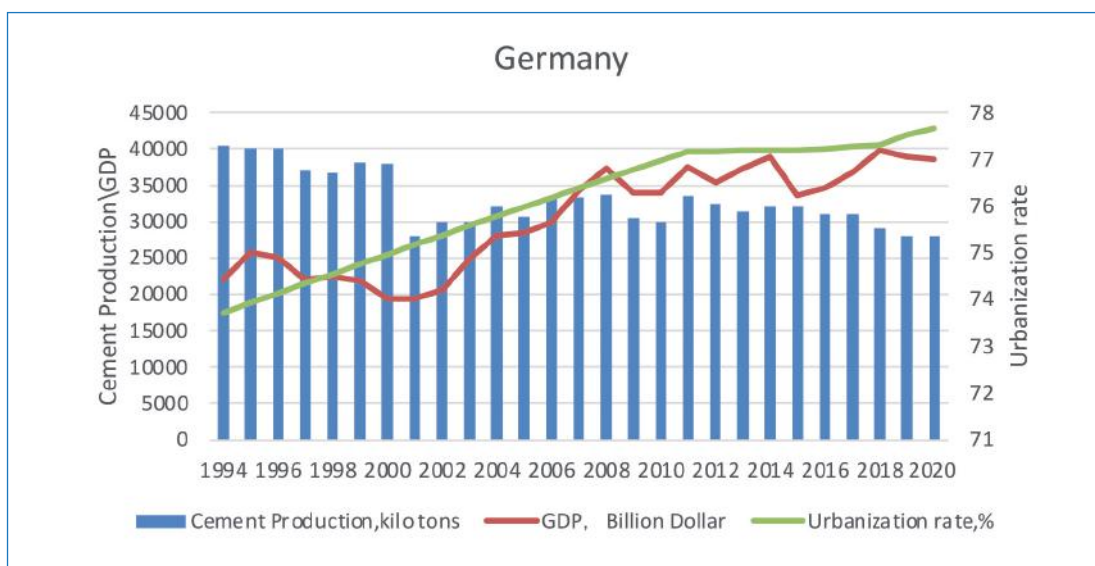


Fig. 5.8. Principal characteristics of the cement industry in Germany<sup>13, 14</sup>

Wood, steel and cement are the 3 major construction materials. Demands for these building materials vary greatly from country to country due to different levels of economic development and resource endowment.

It would be too complicated to take such considerations into account in this chapter on cement. Moreover, the issue of substituting cement by wood or steel is beyond the scope of this report and has thus not been discussed.

<sup>11</sup> U.S. Bureau of Economic Analysis, GDP & population statistics

<sup>12</sup> U.S. Geological Survey, Cement Statistics and Information (<https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information>)

<sup>13</sup> Eurostat, GDP & population statistics

<sup>14</sup> U.S. Geological Survey, Cement Statistics and Information (<https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information>)

## 2. Current situation

The cement industry is one of the largest CO<sub>2</sub> emitting industrial sectors in the world. Bearing in mind that cement is the most widely used material for housing and modern infrastructure, different cement manufacturing process options need to be considered to make cement production more sustainable. With 50% of CO<sub>2</sub> emissions from cement production being purely process related, the industry is not only a source of combustion-related CO<sub>2</sub> emissions, but also the largest source of process-related CO<sub>2</sub> emissions in any industrial sector. The process in question is the calcination process, which contributes about 50% of CO<sub>2</sub> emissions, while the combustion of solid fuels contributes about 40%. The remaining CO<sub>2</sub> (about 10%) is emitted during the transport of raw material and some other production processes that consume electric power<sup>15</sup>.

### 2.1. The cement manufacturing process in brief

#### 2.1.1. Exploitation of raw materials

- Quarry: drilling and blasting techniques are used for the exploitation of limestone, marl and clay. Other materials containing the required ratios of calcium, silicon, aluminium and iron oxides are also exploited.
- Crushing: the material from the quarry is then crushed using different types of mechanical crushers, from the size of 120 cm to 1.2-8 cm. Material drying and pre-homogenisation processes can also be used for efficient crushing.
- Transport: the raw material is then transported to the plant using conveyors, rail wagons, trucks or other specific means of transportation.

#### 2.1.2. Mixing of raw materials and clinkerization

- Mixing: crushed limestone and clay are pre-homogenised by subtraction and backfilling in long layered piles, thus prepared for the grinding and drying process.
- Raw mill: the raw materials are ground and dried in a vertical or ball mill.
- Bag filter: these filter elements made of textile materials remove material particles from the furnace exhaust gases.
- Heat exchanger: the cyclone heat exchanger allows raw materials to be preheated before entering the furnace.
- Rotary kiln: the rotary kiln is designed in such a manner that the energy of fuel combustion is delivered to the raw material as efficiently as possible. In the rotary kiln preheater zone, the raw material is rapidly heated to a temperature of approximately 1 000 °C, during which the limestone turns into quicklime. The thermal decomposition of limestone into quicklime, known as the calcination process, occurs inside the precalciner. In a rotary kiln, temperatures reach up to 2 000 °C, producing cement clinker.
- Cooler: the molten cement clinker is then cooled as quickly as possible in a clinker cooler.

#### 2.1.3. Grinding and distribution

- Clinker silo: the clinker is stored and ground in the factory or transported to other users.
- Cement mill: the final grinding of the cement clinker is done with approximately 5% of natural or artificial gypsum. Other cement admixtures may be added along with such other materials as slag, fly ash, or pozzolana.
- Logistics: the packed cement is then transported by suitable means.

The production process is shown in *Fig. 5.1.*

<sup>15</sup> Mikulčić, H, Vujanović, M, Duić, N. 2013. Reducing the CO<sub>2</sub> emissions in Croatian cement industry. Appl. Energy 101, 41-48. doi: 10.1016/j.apenergy.2012.02.083

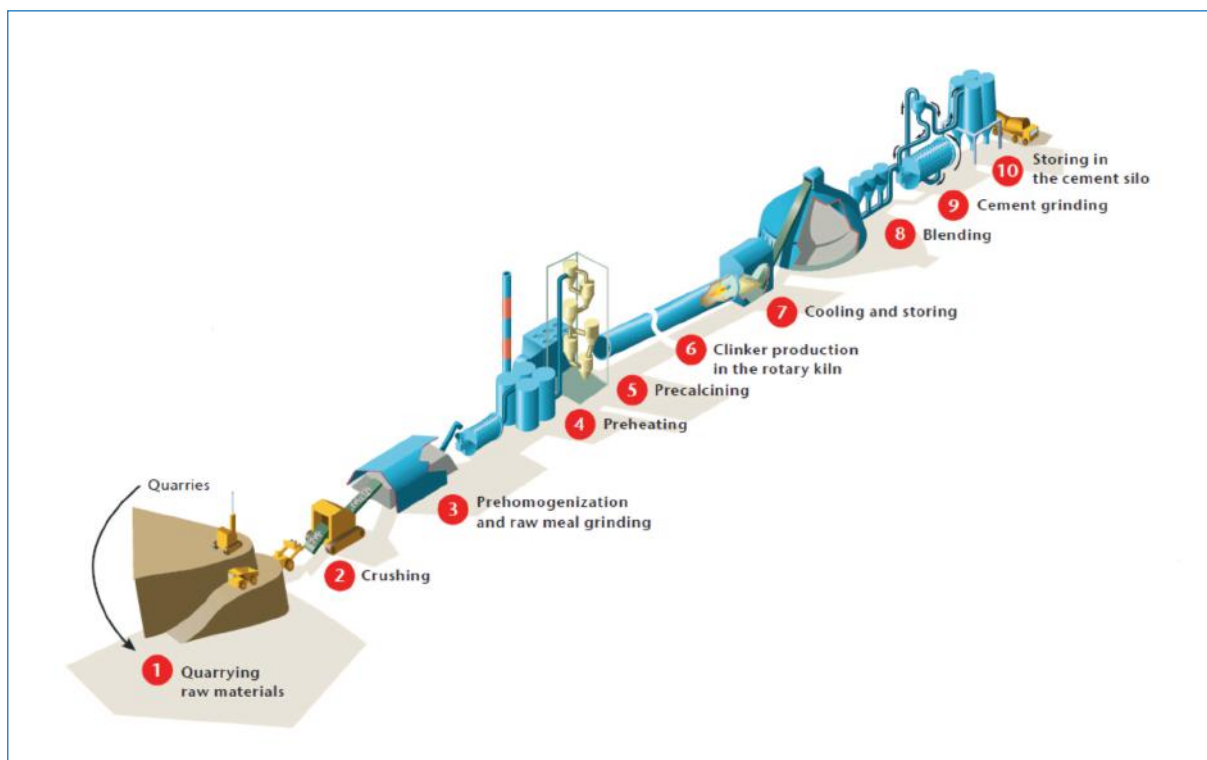


Fig. 5.9. Cement manufacturing process<sup>16</sup>

Multistage cyclone preheating systems with several stages have been developed to enhance heat exchange between the raw material and the flue gases. In other words, the raw material is heated by moving counter to the flow of the hot flue gases coming from the rotary kiln, and repeatedly so until the raw material has gone through all the cyclones.

Once preheated, the raw material (mainly limestone) enters the cement calciner – a combustion unit preceding the rotary kiln. Here the limestone undergoes the calcination process. This process is a strongly endothermic reaction requiring large amounts of energy input.

Clinker burning is the highest energy demanding process in cement production, and it occurs after the calcination process where a temperature of 1 450 °C ensures clinker formation. The cement calciner and rotary kiln are the two combustion units where the endothermic calcination reaction and combustion of different solid fuels occur. As these thermochemical reactions are the main sources of CO<sub>2</sub> emissions from cement production, special care needs to be taken in order to optimise the work load of these units. Following the clinkering process in the rotary kiln, the cement clinker is rapidly cooled down to 100–200 °C. This is done rapidly so as to prevent undesirable chemical reactions. Blending the clinker with different additives follows the clinker cooling process. At that point, the composition of the final product – cement – is obtained. Thereafter, the cement is milled, stored in the cement silo, and distributed to consumers<sup>17</sup>.

As the cement industry is an energy-intensive one, total energy use (thermal and electric) accounts for approximately 50–60% of the total production costs. Thermal energy accounts for about 20–25% of the cement production cost. The typical electric energy consumption of a modern cement plant is about 110–120 kWh per tonne of cement. The main thermal energy is used during the combustion / burning process, while most electrical energy is used for cement grinding as illustrated in Fig. 5.10.

<sup>16</sup> IEA – Technology Roadmap Low-Carbon Transition in the Cement Industry, Page 12:  
<https://iea.blob.core.windows.net/assets/cbaa3da1-fd61-4c2a-8719-31538f59b54f/TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf>

<sup>17</sup> Mikulčić, et al., 2016

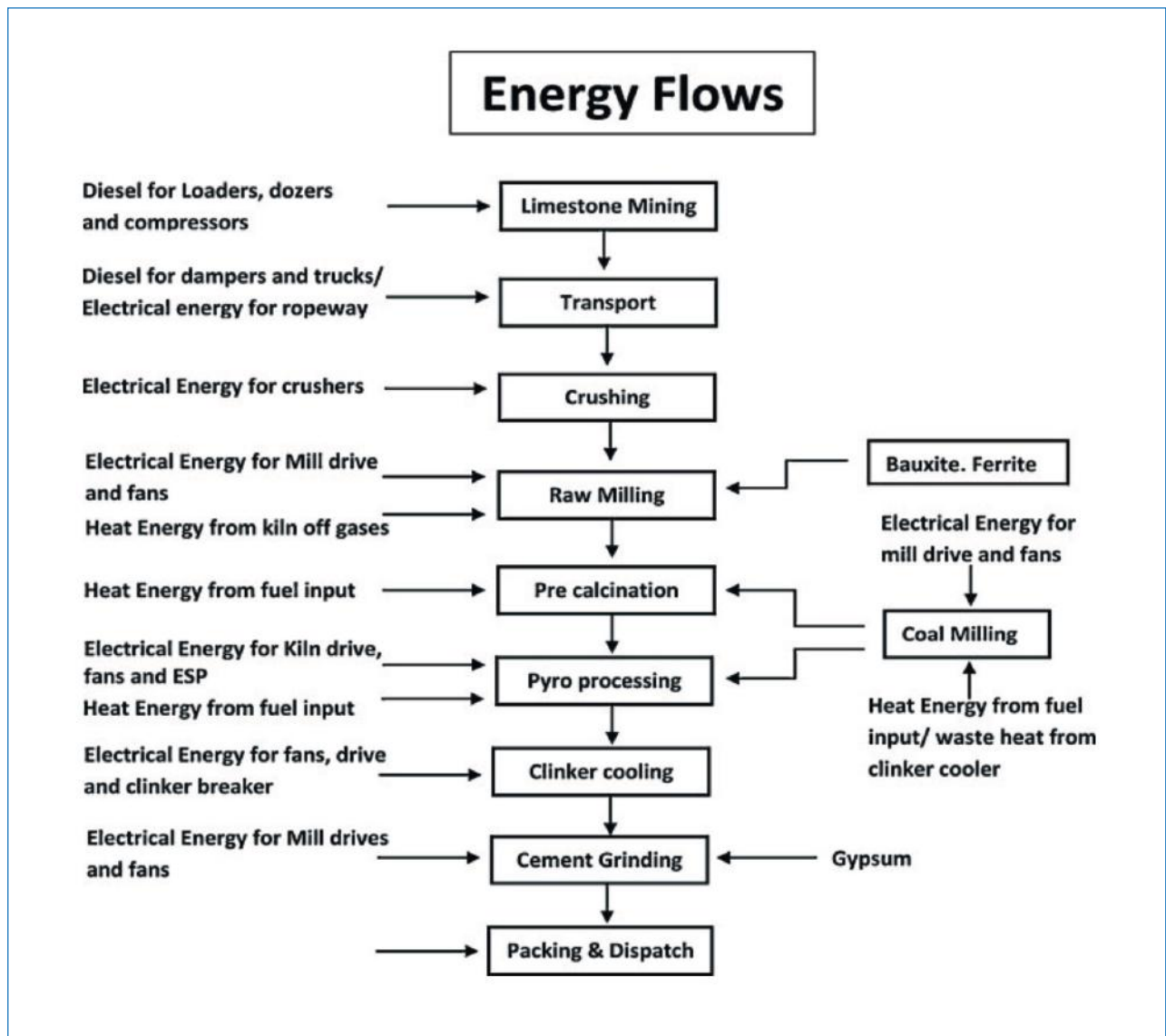


Fig. 5.10. Cement manufacturing process energy flows<sup>18</sup>

<https://www.sciencedirect.com/science/article/pii/S1364032111000207>

## 2.2. Worldwide production

Table 5.1. provides a list of the major cement producers in the world for 2012 and 2020. It shows that by far most of the cement production is located in developing countries, especially in Asia.

<sup>18</sup> Madlool, N. a., Saidur, R., Hossain, M.S., Rahim, N. A. 2011. A critical review on energy use and savings in the cement industries. Renew. Sustain. Energy Rev. 15, 2042–2060. doi: 10.1016/j.rser.2011.01.005

Country	2012		2020	
	Production (Mt)	Share in the world production	Production (Mt)	Share in the world production
China	2 150	58.1%	2 200	51.1%
India	250	6.7%	340	7.9%
United States	74	2.0%	90	2.0%
Brazil	70	1.9%	57	1.3%
Iran	65	1.8%	60	1.4%
Vietnam	65	1.8%	96	2.2%
Turkey	60	1.6%	66	1.5%
Russian Federation	60	1.6%	56	1.3%
Japan	52	1.4%	53	1.2%
South Korea	49	1.3%	50	1.1%
Egypt	44	1.2%	50	1.1%
Saudi Arabia	43	1.2%	Not Available	-
Mexico	36	1.0%	56	1.3%
Germany	34	0.9%	Not Available	-
Thailand	33	0.9%	Not Available	-
Pakistan	32	0.9%	Not Available	-
Italy	32	0.9%	Not Available	-
Indonesia	31	0.8%	73	1.7%
Spain	20	0.5%	Not Available	-
Nigeria	28 <sup>19</sup>	0.76%	58.9 <sup>20</sup>	1.37%
Other (rounded)	472	12.8%	Not Available	-
World total (rounded)	3 700	-	4 300	-

Table 5.1. Global cement production<sup>21</sup>

The importance of cement production in these developing economies can also be observed when comparing the annual CO<sub>2</sub> emissions resulting from cement production in industrialised countries with that in developing countries. In the EU, the cement industry contributes to about 4.1% of total CO<sub>2</sub> emissions<sup>22</sup>. Whereas in China, the largest cement producing country and largest emitter of GHG emissions in the world, 15% of total CO<sub>2</sub> emissions are related to cement production<sup>23</sup>.

<sup>19</sup> Cement Production in Nigeria, Mmemek-Abasi Etim, Atmosphere, 2021.9

<sup>20</sup> Cement Production in Nigeria, Mmemek-Abasi Etim, Atmosphere, 2021.9

<sup>21</sup> Statista, 2021. <https://www.statista.com/statistics/267364/world-cement-production-by-country/> for Major countries in worldwide cement production from 2010 to 2020

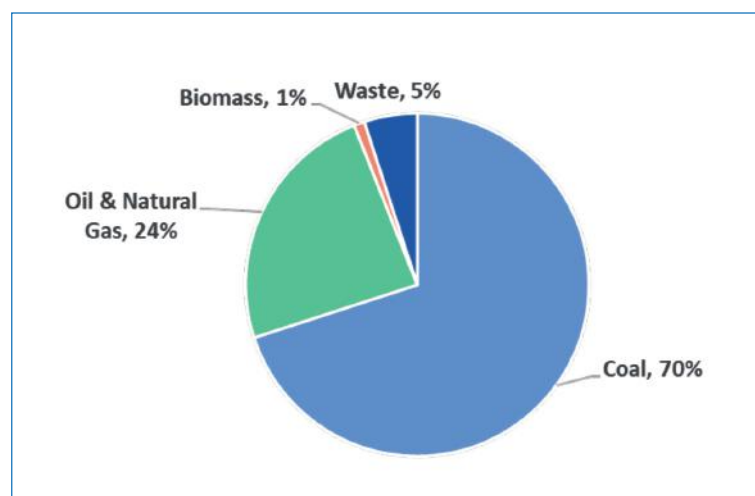
<sup>22</sup> Pardo N, Moya JA, Mercier A. 2011. Prospective on the energy efficiency and CO<sub>2</sub> emissions in the EU cement industry. Energy. 36, 3244-3254. doi: 10.1016/j.energy.2011.03.016

<sup>23</sup> Chen, W., Hong, J., Xu, C., 2014. Pollutants generated by cement production in China, their impacts, and the potential for environmental improvement. J. Clean. Prod. 103, 61-69. doi:10.1016/j.jclepro.2014.04.048

## 2.3. Energy consumption of the cement industry

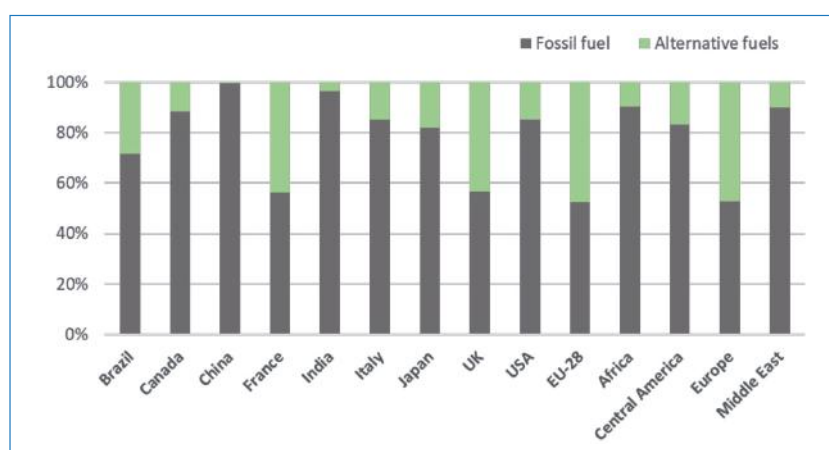
### 2.3.1. Energy source in the cement industry

As already stated and shown in *Fig. 5.11.*, the energy consumption of cement production mainly comes from fossil fuels, such as coal. Major industrialised countries are taking carbon-containing industrial waste and zero- carbon biomass, etc. as alternative fuels for cement production.



*Fig. 5.11.* Fuel mix in the cement industry<sup>24</sup>

The mix ratio of fossil fuels to alternative fuels in cement production varies in different countries, influenced by their respective resource endowments and policies, as shown in *Fig. 5.12.*. France, the United Kingdom, Italy and other European countries, as well as Canada and the United States of America, started using partially alternative fuel technology in cement production earlier. In those countries, fuel pre-treatment technology and alternative fuel technology are widely promoted and applied; their alternative fuel mix ratio is therefore higher. In China, India, the Middle East, Africa and other developing countries and regions, the development and application of alternative fuel technology is not as advanced; thus, fossil fuels still dominate there. In recent years, with the popularisation and application of alternative fuel technology, the mix ratio of alternative fuel has gradually been increasing.



*Fig. 5.12.* Regional thermal energy mix ratio in the cement industry<sup>25</sup>

<sup>24</sup> Source of data: IEA(2018),Technology Roadmap-Low Carbon Transition in the Cement Industry, Page 29

<https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry>

<sup>25</sup> Source of data: Thermal specific energy consumption per tonne of clinker in selected countries and regions, 2018 – Charts – Data & Statistics - IEA  
<https://www.iea.org/data-and-statistics/charts/thermal-specific-energy-consumption-per-tonne-of-clinker-in-selected-countries-and-regions-2018>

### 2.3.2. Energy transition trend in different countries

The major cement-producing countries are actively implementing clean energy policies and carbon-reduction technologies. As it is being developed, clean energy, such as wind, solar and nuclear power, can be used as a source for electricity to reduce indirect emissions. Hydrogen energy can be used as an alternative fuel to replace fossil fuels in the cement calcination process, thus theoretically reducing carbon emissions by about 30%. Concentrated solar energy is also an object of research for cement calcination. The energy transition strategies of different countries are shown in *Table 5.2*.

Country / Region	Energy improvement strategies
United States of America	The USA replace coal by gas in power generation, deploy and increase the proportion of offshore wind and solar power generation; start hydrogen energy research projects such as electrolytic water to hydrogen equipment, biological hydrogen research, and electrochemical hydrogen production.
France	France plans to restart nuclear power construction and promotes hydrogen energy technology research and development and industrial applications.
Germany	Germany passed legislation to close nuclear power plants, confirms the priority development of green hydrogen.
China	China is improving the clean and efficient use of coal; vigorously plans to build a low-carbon system using wind and solar energy; each province successively proposed to develop its hydrogen energy industry.
India	While India plans to increase clean energy with enhanced nuclear power capacity, it is rigorously pursuing solar and wind energy aiming at 50% energy requirement from renewable energy (RE) in about a decade.

*Table 5.2.* Energy transition strategies of different countries

## 2.4. CO<sub>2</sub> Emission in the cement production

### 2.4.1. CO<sub>2</sub> emission intensity of the cement production

As already stated, in the cement production process, nearly 90% of CO<sub>2</sub> emitted results from two thermochemical processes. Taking China's cement industry as an example, *Table 5.3* displays energy consumption, emission intensity and CO<sub>2</sub> emission at each of these steps

Item	Unit consumption	Emission factor	Emission of CO <sub>2</sub>	Percentage	Percentage Note
Fuel consumption per unit of cement	69 kg/tonne coal equivalent	~2.66 kg/kg coal equivalent	183.5 kg/tonne	~32.9%	direct emission
Electricity consumption per unit of cement	97~120 kWh/tonne	~0.8kg/kWh	77.6 ~96kg/tonne	13.8%~16%	indirect emission
Limestone consumption per unit of cement	754~840 kg limestone/tonne	~0.44 kg/kg limestone	301.6~336 kg/tonne	53.6%~55%	process emission
<b>Total emission</b>	<b>562.7~615.5 kgCO<sub>2</sub>/ton cement</b>				

*Table 5.3.* CO<sub>2</sub> emission from cement production in China<sup>26</sup>

<sup>26</sup> Preliminary study on the utilisation of hydrogen energy in cement clinker burning, Wanglan, 2021 International Forum on Carbon Emission Reduction in the Building Materials Industry

### 2.4.2. CO<sub>2</sub> emission intensity of clinker for different countries

The global carbon emission intensity of cement clinker ranges between 815 and 880 kg/tonne cement clinker. CO<sub>2</sub> emission intensity varies notably among different countries, mainly because of differences in access to and use of carbon emission reduction technology. For example, India has a relatively high proportion of alternative raw material usage and a low proportion of cement clinker, so that CO<sub>2</sub> emission intensity is rather low. The increase of carbon emission intensity in Egypt is due to a fuel switch from natural gas to coal, resulting from increasing costs and the removal of government fuel subsidies. The general trend however, with the global promotion and application of energy-saving and emission reduction technologies, is an annual decline in CO<sub>2</sub> emission intensity.

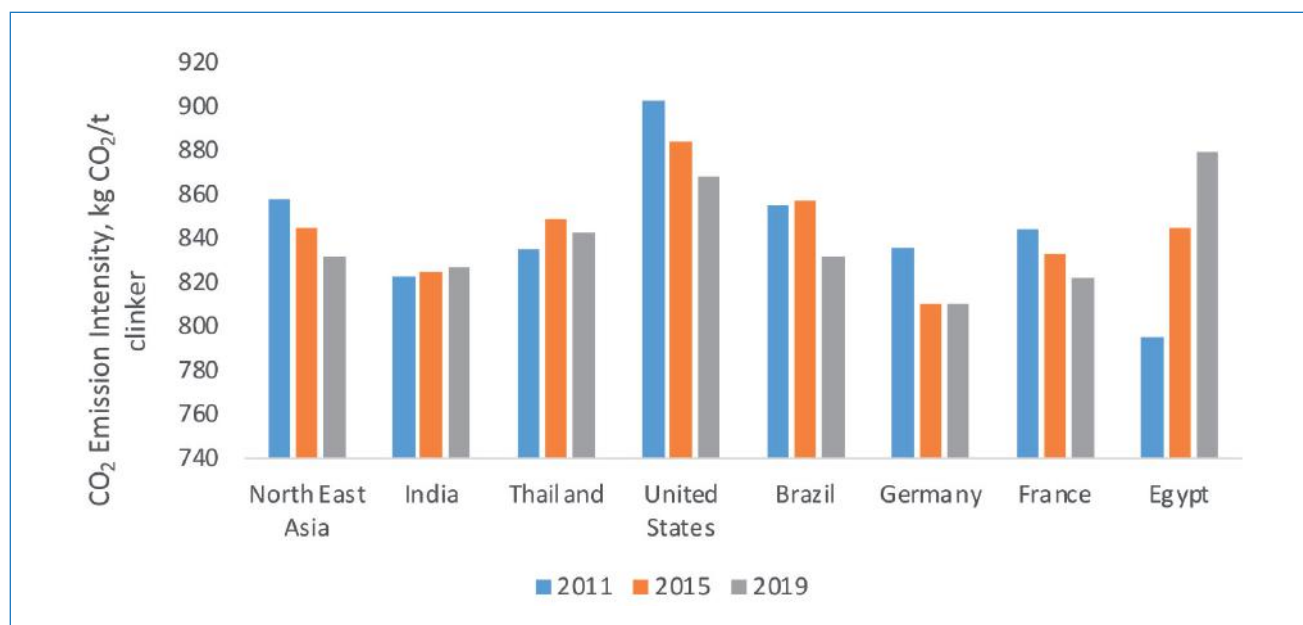
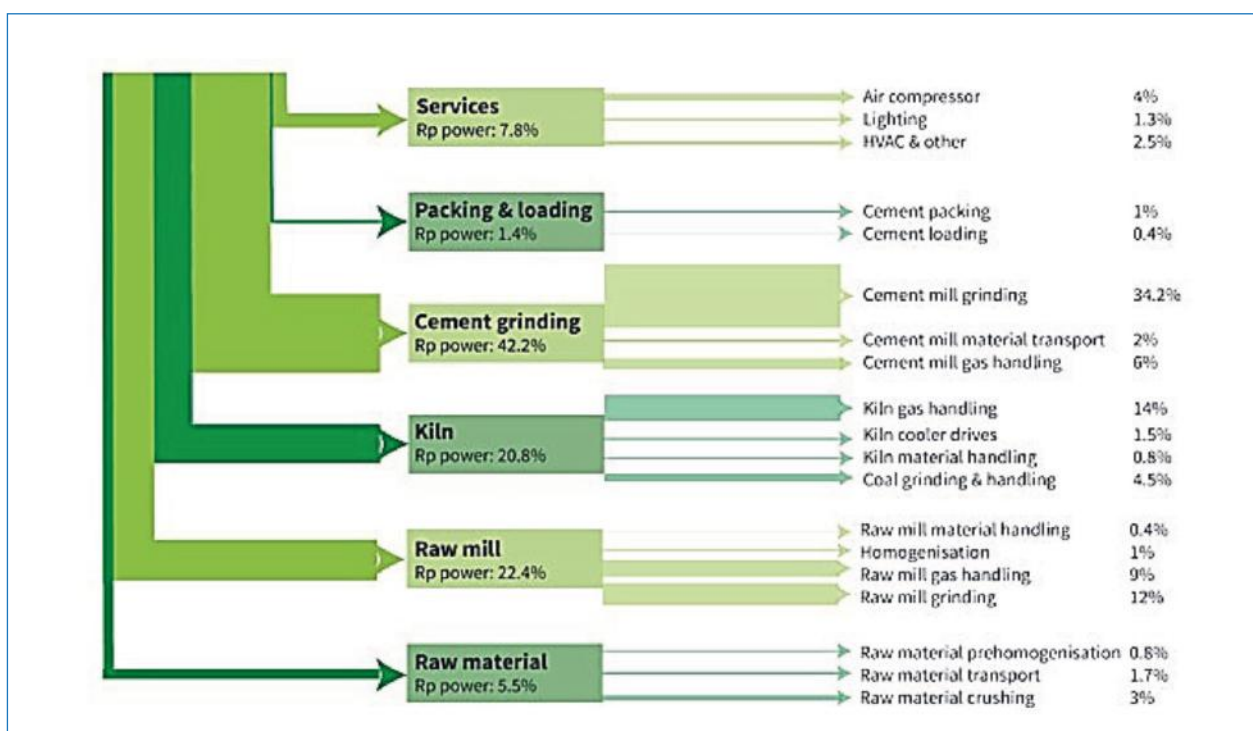


Fig. 5.13. CO<sub>2</sub> emission intensity of clinker for different countries<sup>27</sup>

<sup>27</sup> Data source: GCCA GNR Data base, Gross CO<sub>2</sub> emissions—Weighted average excluding CO<sub>2</sub> from on-site power generation—Grey clinker.



- A typical breakdown of electrical energy consumption at a cement plant is shown in *Fig. 5.16.* Grinding of material is generally an inefficient process. Grinding aids, which are organic compounds, may be added to the mill during cement grinding. Their main purpose is to reduce the energy required to grind the clinker into a given fineness.<sup>30</sup> They can increase production by 5 to 15% but need to be continuously evaluated for cost effectiveness. Unfortunately, their cost has been rising more rapidly than the cost of energy in recent years; the economic balance has thus to be re-evaluated. The benefit of aids on cement flowability has to be considered, along with the added scope for reduction of cement clinker content with some modern additives. Accurate process measurements are also key to energy saving opportunities.
- In addition, some products (usually referred to as performance enhancers) provide positive effects on cement hydration, improving strength development.



*Fig. 5.16.* Breakdown of electrical energy consumption at a typical cement plant<sup>31</sup>

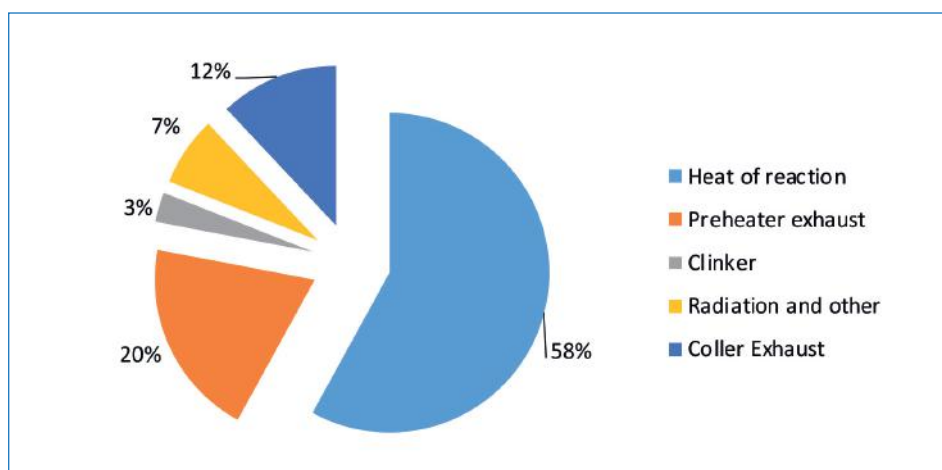
In the following list, different forms of waste heat recovery and usage are described in addition to other efficiency enhancements:

- Dry kilns with multistage pre-heaters and pre-calcination make use of the waste heat from the kiln and clinker cooler to preheat and pre-process the kiln feed. The cyclone heat exchanger allows raw materials to be preheated before they enter the furnace and increases the energy efficiency of the furnace, so much so that the material is already 20-40% calcined when entering the furnace.
- The bag filter (whose filter elements are made of fabric) removes material particles from the furnace exhaust gases. The exhaust gases of multiple kilns are used to dry the raw material, thus increasing energy efficiency.
- Process control and optimisation in clinker making: high efficiency motors and drives, as well as high-efficiency classifiers / separators, will improve the operation process and save energy. Atmospheric air is used to cool the clinker and then used in the rotary kiln as combustion air ensuring the high efficiency of the heat produced.

<sup>30</sup> [http://cadd.mapei.com/wp-content/uploads/2016/03/2010-09-Mapei\\_Paper\\_ICR\\_Sept-2010.pdf](http://cadd.mapei.com/wp-content/uploads/2016/03/2010-09-Mapei_Paper_ICR_Sept-2010.pdf)

<sup>31</sup> The Cement Plant Environmental Handbook (2<sup>nd</sup> Edition), International Cement Review, Tradeship Publications Ltd (UK)  
<https://www.cemnet.com/Articles/story/156121/best-energy-consumption.html>

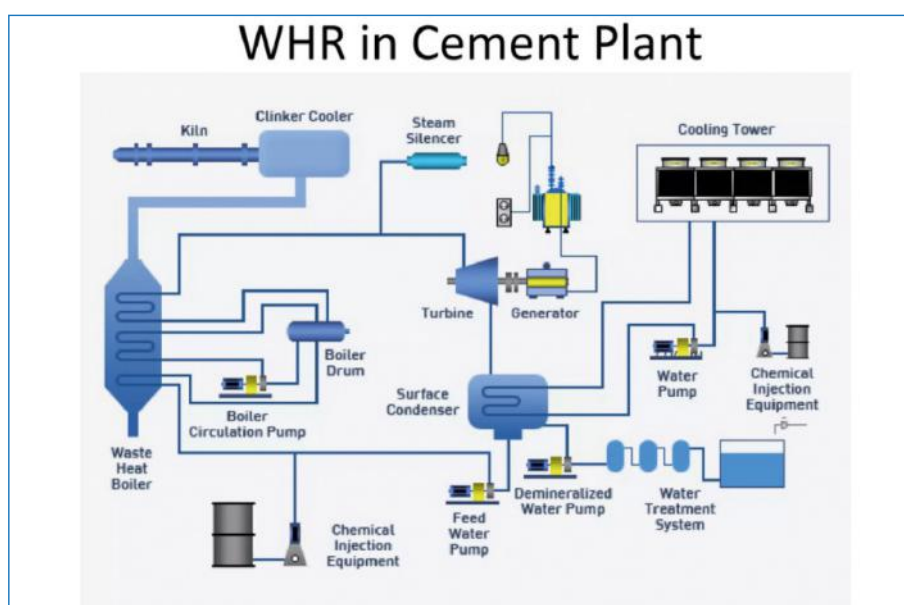
- Efficient transport systems (dry process): Mechanical conveyors use less power than pneumatic systems. Further optimisation of the overall transport system in general can be obtained using AI and machine learning as well as through modernisation of the fleet.
- Raw meal blending (homogenising) may reduce heat requirements by 2.11 MJ/tonne clinker and power requirements by 0.73 kWh/tonne raw materials, while production could increase by 5%.
- Waste Heat Recovery (WHR) can also be used for electricity generation. Such power plants can be installed alongside cement plants. They use the heat that is generated through the rotary kiln Preheater (PH) and Air Quenching Cooler (AQC) to exhaust hot gases for power generation, thus reducing the consumption of fossil fuels. Waste heat sources in cement plant are shown in *Fig. 5.17.*



*Fig. 5.17.* Waste heat sources in cement plant

WHR has great potential to generate about 20 to 30% of plant power requirements (by reducing purchased / captive power needs). The electricity generated in the cement plant would thus not be sufficient to meet its electricity requirements. It is one of the cheapest sources for electric power generation, given the negligible input costs.

The most commonly used waste heat recovery methods are preheating combustion air, steam generation (*Fig. 5.18.*) and water heating, and load preheating.



*Fig. 5.18.* Waste heat recovery system in the cement plant<sup>32</sup>

<https://www.slideshare.net/AbdulHaseeb60/waste-heat-recovery-system-in-cement-plant>

<sup>32</sup> Abdul Haseeb, Waste Heat Recovery System In Cement Industry, Health Safety & Environment, Summer-2015 GSESIT-FEST Hamdard University, slide 6

Some plants in India have installed WHR and generated 400 MW of WHR-based power, thus saving around 2.2 Mt of coal.

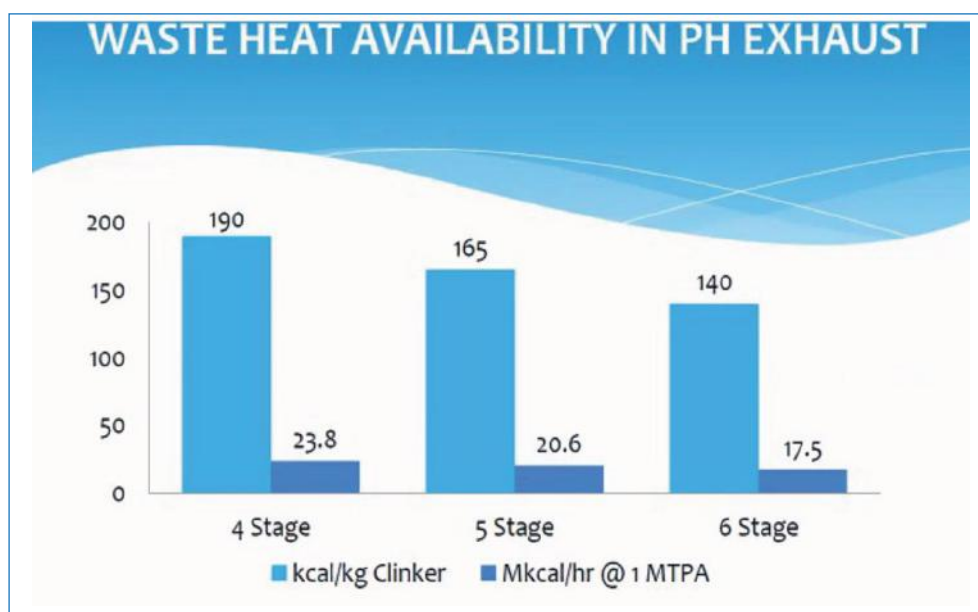


Fig. 5.19. Waste heat availability in PH exhaust<sup>33</sup>

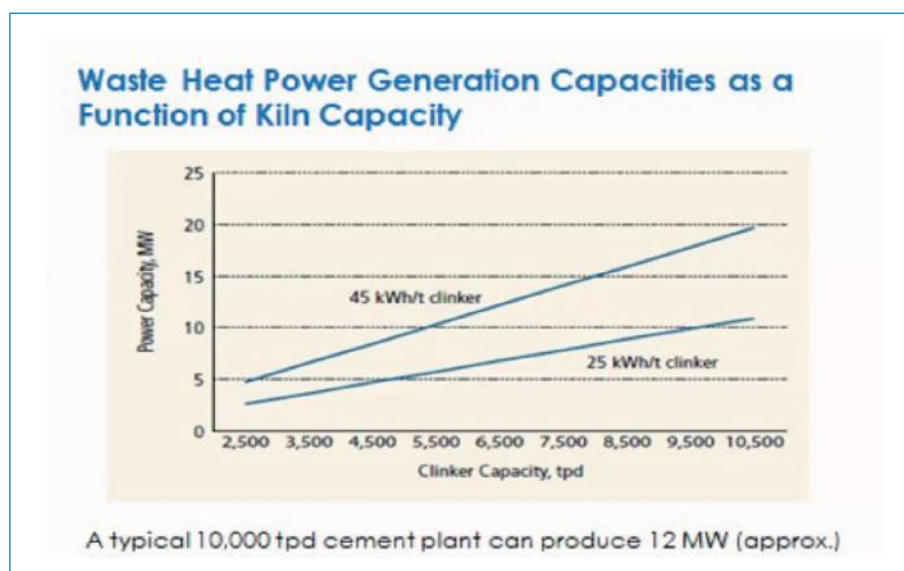
REQUIRED HEAT FOR RAW-MILL AT DIFFERENT KILN CAPACITY									
1	Kiln capacity	TPD	2000	3000	4000	5000	6000	7000	8000
2	Raw mill requirement	TPD	3382	5073	6764	8455	10145	11836	
3	Heat requirement	Mkal /hr							
a	@ 2% moisture		1.6	2.4	3.2	4.0	4.8	5.7	6.5
b	@ 4% moisture		5.6	8.4	11.2	13.9	16.7	19.5	22.3
c	@ 8% moisture		11.6	17.5	23.3	29.1	34.9	40.7	46.6
d	@ 12% moisture		18.3	27.4	36.5	45.6	54.8	63.9	73.0

Fig. 5.20. Raw-mill heat requirements at different kiln capacities<sup>34</sup>

<sup>33</sup> ICC E-Conference on Cement Industry - 4<sup>th</sup> Cementing India - 2021

<sup>34</sup> ICC E-Conference on Cement Industry - 4<sup>th</sup> Cementing India - 2021

HEAT REQUIREMENT FOR CEMENT ADDITIVES				
Characteristics of Cement Additives (other than Limestone)				
S.No.	Material	% of addition in Cement	% moisture level	Heat requirement
<b>1</b>	<b>Gypsum</b>	3-5%		
a	Chemical		8-20	Met from grinding & clinker heat
b	Salt Pan			
c	Mineral		3-10	
<b>2</b>	<b>Fly ash</b>	15-35%		
a	Dry Fly Ash		<2%	Not needed
b	Wet Fly Ash		15-30%	Significant extra heat required
<b>3</b>	<b>Slag</b>	35-65%	<12%	Significant extra heat required

Fig. 5.21. Heat requirements for cement additives<sup>35</sup>Fig. 5.22. Waste heat power generation capacities as a function of kiln capacity<sup>36</sup>

For the temperature profile available in the WHR plant cement industry, cycle efficiency for the Rankine cycle is around 22%, whereas efficiency for ORC and Kalina cycles are 35% and 60% respectively.

However, experiences in the WHR process encounters barriers, such as the presence of dust, uninterrupted supply of hot gas, false air ingress in the PH boiler operating in negative pressure and low financial return.

Operational improvements can be achieved by altering the operating procedures at an existing plant, with no significant capital investment.

The use of energy monitoring and process control systems embracing digital technology (AI, neural networks) with Computer-Integrated Manufacturing (CIM) can play an important role in energy management and in reducing energy use and increase the potential for greater clinker replacement in the future.

<sup>35</sup> ICC E-Conference on Cement Industry - 4<sup>th</sup> Cementing India - 2021

<sup>36</sup> ICC E-Conference on Cement Industry - 4<sup>th</sup> Cementing India - 2021

Examples of Circular Economy in the cement industry are: required gypsum may be generated from flue gas desulphurisation (FGD) in a Thermal Power Plant (TPP), the use of fly ash from thermal power plants for high-volume fly ash cement, the use of steel granulated slag from iron-making, the reduction of the clinker factor with alternative raw materials, and the increase of the Thermal Substitution Rate (TSR) with the use of alternative fuels, such as non-recyclable plastic waste. Such methods help improve energy efficiency and cost savings. The current average TSR in the Indian cement industry has risen to 4% from less than 1% a couple of years ago. The industry is now working towards reaching a TSR of 25% by 2025 and 30% by 2030. Optimising the performance at the global level represents a potential for improvement up to 100 Mt CO<sub>2e</sub> per year. Airflow and fuel type were found to dominate the variation of performance.

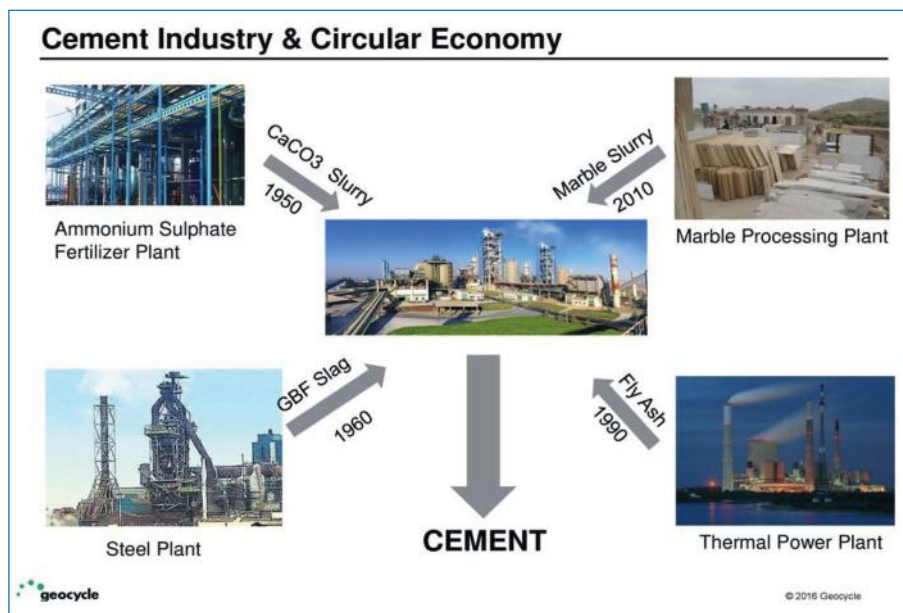


Fig. 5.23. Cement industry and circular economy

Eric Thomson, Environmentally Sound Management of Plastics Wastes through Cement Kiln Co-processing Ulhas Parlikar Dy Head, Geocycle India ACC Limited 2016-04-14.

<https://slideplayer.com/slide/14094617/>

### 3.2. Alternative raw materials

Substituting limestone with alternative calcium containing decarbonated raw materials (e.g. blast furnace slag, lignite ash, coal ash, concrete crusher sand, aerated concrete meal, demolition waste, construction waste, ceramic moulds, refractory bricks, road sweepings, etc.) is an attractive option for reducing CO<sub>2</sub> emissions, with the dual advantage of 1) linking the reduction of emissions to the degree of the prior decarbonation of raw materials and 2) reducing the fuel required for decarbonation to the extent that the material is already decarbonated. Below are indicated alternative raw materials.

- **Steel slag:** as the energy required for calcination is estimated to be 1.9 GJ/t (0,53 MWh/t) clinker, substituting 10% of clinker with steel slag will reduce energy consumption by 0.19 GJ/t (53 kWh/t) clinker. Replacing 10% of clinker by steel slag can reduce CO<sub>2</sub> emissions by approximately 11%.
- **Calcareous oil shale:** oil shale can replace up to 76% of raw materials in clinker manufacturing, which is sufficient for calcination and final burning in a rotary kiln. This means that oil shale can partially replace fuel, reducing CO<sub>2</sub> emissions during clinker production and energy consumption can be reduced by around 0.7 GJ/t (190 kWh/t) Portland cement.
- **Carbide slag:** Calcium Carbide Residue (CCR), a by-product of the hydrolysis of calcium carbide, is generated from the industrial production of ethylene, polyvinyl chloride (PVC) and other products as a solid waste. Based on alkaline-activated effects, carbide slag is also mixed with fly ash, granulated blast furnace slag or other potentially active materials to produce binder. The slag mainly consists of Ca(OH)<sub>2</sub>. The environmental issues with carbide slag are that if the carbide slag is stacked on the spot, it may pollute water resources near the stacking field, which is a concern, and the drying of carbide slag generates dust, which pollutes the atmosphere.

- Along with the phasing out of coal, **Supplementary Cementitious Materials (SCMs)** such as fly ash, burnt rice husk, and Ground Blast Furnace Slag (GBFS) will decrease in supply.
- **Hydraulic cements** have higher early-age strength, while pozzolana continues to gain strength for longer periods, as it provides higher long-term concrete strength. Both have been proven in construction applications.

	Type of SCMs	Source	Availability	Grindability	Comments
Hydraulic SCMs	GBFS	By-product of steel production	Available in industrialised countries, but as iron and steel production grows more efficient, availability of GBFS will diminish.	High, varies between 120-200% of clinker	Can be substituted up to 100% (70% is common).
Pozzolan-ic SCMs	Fly ash	By-product of coal combustion for power	Around 900 million t/yr available, but only about a third of this is of high enough quality for use in cement and concrete.	Low to moderate, 30% clinker	As coal is expected to diminish, fly ash is not a long-term solution. However, it will take some time, and the developing world will be able to reduce this waste stream for decades to come.
	Calcined clays	Naturally occurring worldwide	Widely available, sometimes even stockpiled as waste from ceramics manufacturing	Easy, <30% clinker	Previously, colour control was an issue, but this has been resolved with the development of new technology from FLSmidth.
	Natural pozzolans	Naturally occurring worldwide	Availability & applicability varies	Varies, 30% -100% clinker	Can be very abrasive and may require finer particle size
	Limestone	Naturally occurring worldwide	Widely available	Low, 30% of clinker	Its use as a filler is regulated in varying amounts from 5 to 35% and has proven effective in greater quantities with proper grinding.

Table 5.4. Common types of Supplementary Cementitious Materials (SCMs)

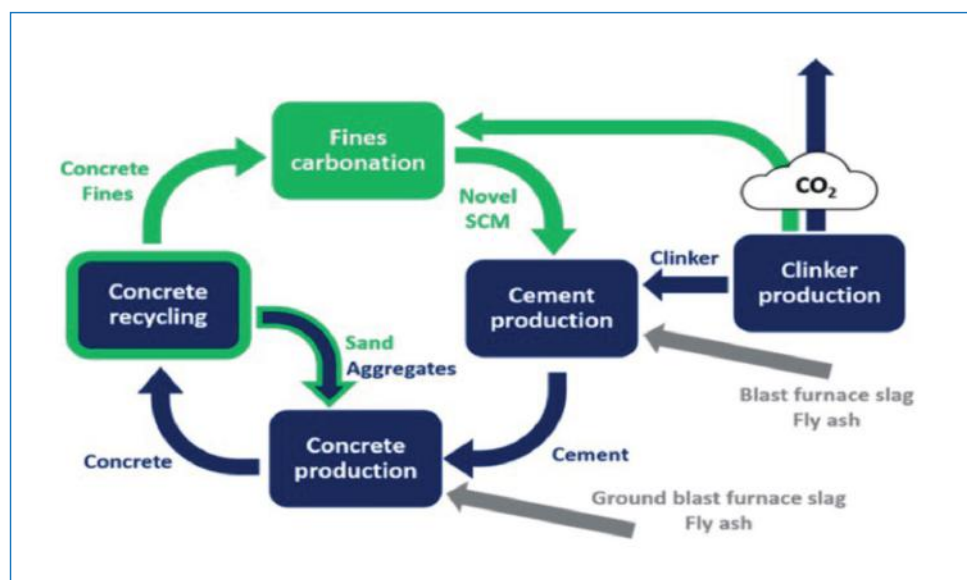


Fig. 5.24. Cement production with substantially lower CO<sub>2</sub> emissions<sup>37</sup>  
<https://www.nature.com/articles/s41598-020-62503-z>

<sup>37</sup> The green colour highlights improvements to the process compared to the current situation shown in blue. The gray colour highlights the traditional supplementary cementitious materials input with uncertain future availability ([nature.com/articles/s41598-020-62503-z](https://www.nature.com/articles/s41598-020-62503-z))

- Limestone Calcined Clay Cement (LC-3): LC3, a new type of cement technology with finer pore structure and high chloride binding capacity developed in Switzerland, is based on a blend of limestone and calcined clay. It can reduce CO<sub>2</sub> emissions by up to 40% and is durable against corrosion, sulphate attacks and other deterioration mechanisms, making it suitable in aggressive conditions.

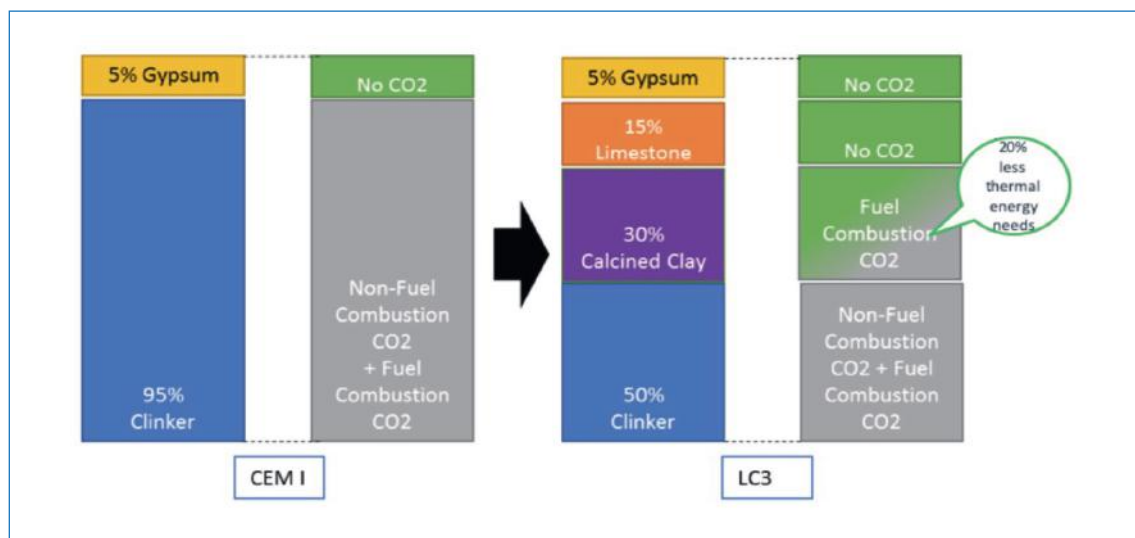


Fig. 5.25. CO<sub>2</sub> emission comparison - CEM I and LC3<sup>38</sup>

LC3 – Limestone Calcined Clay Cement

<https://lc3.ch/why-lc3/>

It will be economical to produce LC3 at most locations when and / or where good quality fly ash is easily available. CO<sub>2</sub> emissions from LC3 production are expected to be 30% lower than OPC (Ordinary Portland Cement) and 11% lower than PPC (Portland-Pozzolana Cement). Energy consumption in its production is also lower than OPC and PPC.

Calcined clay is abundantly available and allows for substitution rates up to 50%. About 40 cement companies in 25 countries are now considering it.

### 3.3. Alternative fuels: waste, biomass, green hydrogen and others

Alternative fuels include the following (see Fig. 5.26. below)

- Municipal Solid Waste (MSW), Solid Recovered Fuel (SRF) / Refuse Derived Fuel (RDF), used tires & mixed plastic waste. One of the most favourable MSW management strategies is thermal treatment or energy recovery to obtain cleaner low-carbon energy. Among many waste-to-fuel strategies, SRF as substitution to fossil fuels is considered advantageous for the cement industry. Higher fossil fuel prices are forcing cement plants to consider the use of SRF for clinker production with a significant reduction in GHG emissions.
- Sewage sludge. This is an organic residue with appreciable quantities of silica and sand, generated by municipalities following the secondary and tertiary treatments of wastewater streams. It can be used in cement production by blending its incinerated ash with Portland cement or by generating co-combustion before adding it to Portland cement.

Both above processes could be implemented to replace Portland cement and would allow for some energy recovery. Energy produced during sewage sludge incineration strongly depends on the water content of sludge and on furnace performance, although its calorific value is close to that of fossil fuel.

<sup>38</sup> [lc3.ch/why-lc3/](https://lc3.ch/why-lc3/)

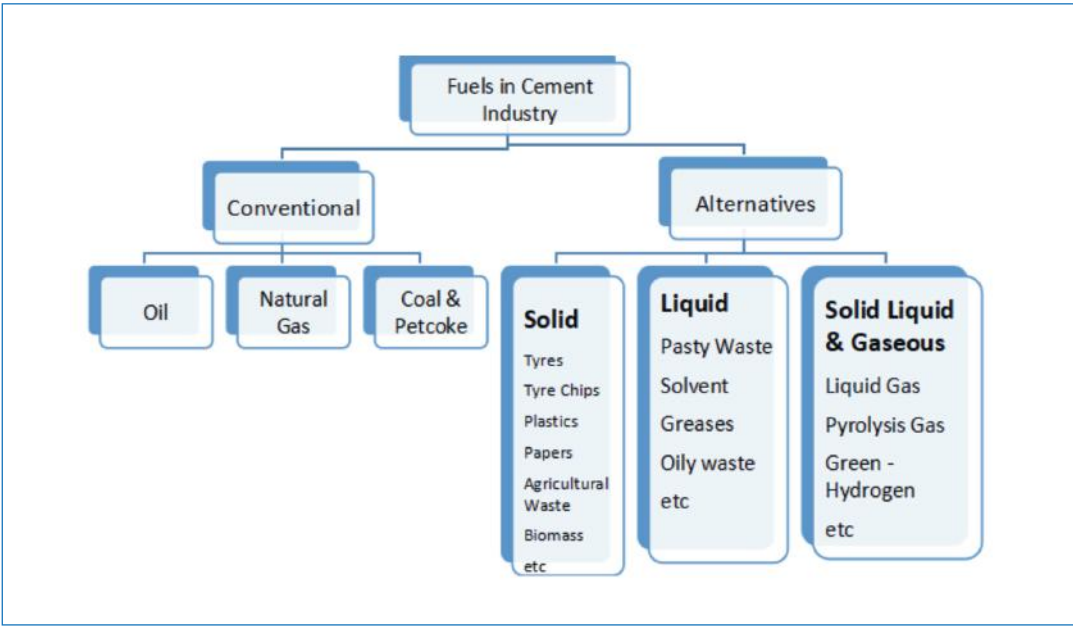


Fig. 5.26. Fuels in the cement industry<sup>39</sup>

Source: Alternative fuels mixture in cement industry kilns employing Particle Swarm Optimization algorithm, Ricardo C. Carpio, Francisco de Sousa Júnior, Leandro dos Santos Coelho, Rogério José da Silva, Journal of the Brazilian Society of Mechanical Sciences and Engineering

Test results have shown that SRF / RDF has no adverse effect upon the emissions and internationally complied with Kyoto Protocol measures and can be used as an Alternativ Fuel (AF).

Superior blends of Food Residue Biofuels (FRB) with paper residues improve clinker production and emissions. Drying Food Residue Biofuels to less than 15% moisture provides a stable, non-hazardous substitution in cement kilns decreases the carbon emission level of clinker.

Plastic waste is considered as one of the most readily available potential candidates as alternative fuel in the cement industry, as it is produced worldwide and has a high calorific value of 29 to 40 MJ/kg (8,1 to 11,1MWh/kg). Plastic waste is available as municipal waste as well as industrial waste. The only concern in using it is the chlorine content which is mainly found in PVC.

AF has a CO<sub>2</sub> reduction potential of 12%. The most effective way to achieve a low CO<sub>2</sub> emission factor will be to use alternative fuels with a ratio value below 25–26%.

Currently available common alternatives to coal / petcoke, oil, or gas include waste, chlorinated hydrocarbons, solvents, plastic, used tires, sewage sludge, etc. (Fig. 5.26.).

<sup>39</sup> [scielo.br/j/jbsmse/a/y5KzJMgcDv8xvWZ9zxbvqr/?lang=en](https://scielo.br/j/jbsmse/a/y5KzJMgcDv8xvWZ9zxbvqr/?lang=en)

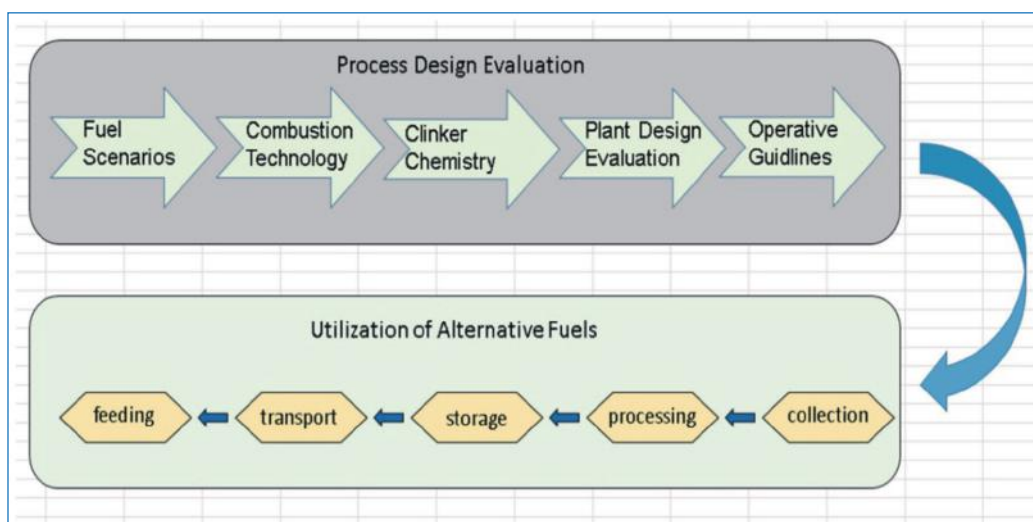


Fig. 5.27. Usage of alternative fuel<sup>40</sup>

Zieri, W., Ismail, I. (2019). Alternative Fuels from Waste Products in Cement Industry. In: Martínez, L., Kharissova, O., Kharisov, B. (eds) Handbook of Ecomaterials. Springer, Cham.

- Biomass

Biomass is one of the most extensively used alternative materials in the cement industry because of its diversity and volume. The major restrictions to the use of biomass in cement manufacturing are linked to economic factors, the necessity of pre-treatment stages, and the local availability of the resources or the transport costs, which are less restrictive than technical limitations. Although replacement ratios of approximately 20% are recommended to maintain a stable combustion process and the quality of the clinker, higher values have been used with very satisfactory results. This could be a cost saving way to reduce the use of fossil fuel and a friendly method of waste management.

- Meat and Bone Meal (MBM)

After the use of MBM was banned in 1994 by the European Union, both as cattle feed and landfilling, interest has been growing in using MBM as fuel in the cement industry. Nowadays in France about 45% of the annual production of MBM is burnt in cement plants. The feeding rates of MBM in cement kilns vary from country to country. MBM has a heating value of 14.5 MJ/kg (4.0 MWh/kg) which is almost half that of coal. Another disadvantage of using MBM as fuel in the cement industry is moisture content, which is about 70%. Hence, pre-treatment is required to reduce it, increasing the processing cost.

- Used oils

Waste oil is hazardous waste originating from automotive, railway, marine, farm and industrial sources. In the European Union, approximately 1 million tonnes of waste oil is used by cement kilns as alternative fuel. Solvent and spent oil from different industries generally have high calorific value and those can be used in cement kilns as alternative fuel with minimal processing cost. The range of calorific value of solvents and spent oil is between 29 to 36 MJ/kg (8,1 to 10 MWh/kg), a variation that is due to their different chemical compositions.

Although used oils have high calorific value and minimal processing costs, their use should be avoided. They are sources of different pollutants and emissions, compared to the use of coal in rotary kilns.

- Low - carbon hydrogen (only emitting water when burned):

Low-carbon hydrogen (see annex hydrogen at the chapter “to set the scene”) may be used to generate methane, which can then be used within the cement making process to fire the burners and to support decarbonisation. The figure below is showing the case of green hydrogen (produced by renewable sources).

<sup>40</sup> [https://doi.org/10.1007/978-3-319-68255-6\\_142](https://doi.org/10.1007/978-3-319-68255-6_142)

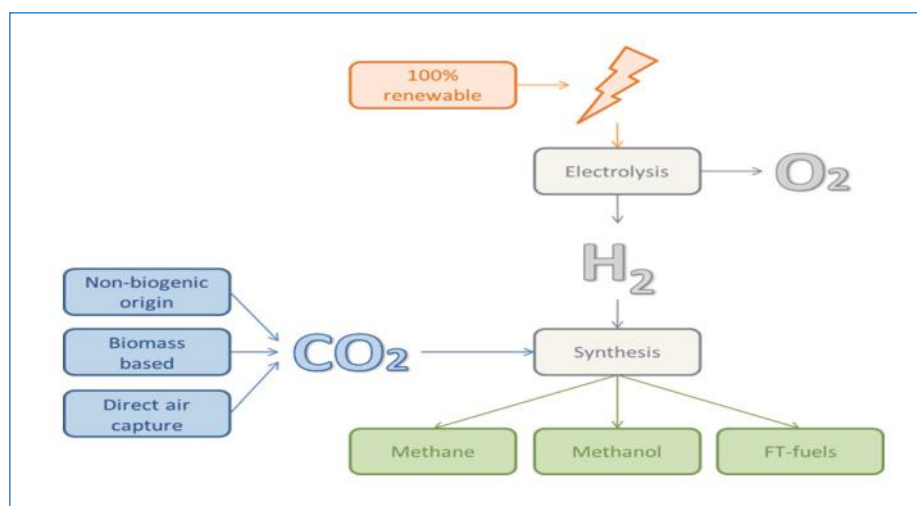


Fig. 5.28. The use of electrofuels

ETP Bioenergy -European Technology and Innovation Platform, Copyright ETIP-B  
Overview on Electrofuels (etipbioenergy.eu)

<https://www.etipbioenergy.eu/overview-on-electrofuels?highlight=WylJbGVjdHJvZnVlbHMlClnZWxlY3Ryb2Z1ZWxzJyJd>

Electrolysis uses water to produce pure hydrogen and oxygen gases. Pure oxygen can be added when burning fossil fuels for more efficient combustion, which would also eliminate the generation of nitrogen oxide by-products (greenhouse gases). Alternatively, the hydrogen and oxygen could replace fossil fuels entirely. However, every MJ of hydrogen produced by electrolysis requires 30% more energy input than it can deliver through final thermal output.

Moreover, as per the latest research, hydrogen has a limited use in producing cement. While it can substitute some of the fossil fuels used in the sector, it cannot be used as an ingredient or reactant in conventional cement production. Other drawbacks also restrict its usage, as hydrogen:

- is highly flammable – more so than regular fuel – and harder to contain;
- is currently more expensive to produce than hydrogen from natural gas
- is difficult to store and transport;
- needs new infrastructure, while replacing the existing one is not easy.

By replacing some of the coal or natural gas used, employing low-carbon hydrogen as a fuel could reduce some of the emissions from the cement industry. However, the properties of the flame generated by the combustion of hydrogen, such as heat dispersion, are different from the heat resulting from the conventional fuels being used. As a result, hydrogen might not be adequate to heat the cement kiln or suitable for the burner used in clinker production. To address these limitations, researchers are currently focusing on combining hydrogen with other low-carbon fuels such as biomass.

Furthermore, cement-making technologies can be combined with carbon capture and storage. Applying technologies that separate the process gases from the combustion gases (i.e. the LEILAC project) would enable low-cost carbon capture for storage. At the same time, it would facilitate the use of an alternative fuel such as hydrogen. Such a combination of decarbonisation technologies, once feasible, would tackle all emissions from cement production and achieve deep reductions in the sector.

- Solar energy

Licht et al., (2012) developed a method for cement production called Solar Thermal Electrochemical Production of cement, or STEP cement. This method releases zero CO<sub>2</sub> emissions, using solar thermal energy instead of the fossil fuel as a heat source.

Solar heat is used to melt the limestone and also provides heat for the electrolysis of the limestone. During the electrolysis, depending on the temperature of the reaction, current applied to the limestone (CaCO<sub>3</sub>) changes the chemical reaction of limestone decomposition.

When separated, the carbon and oxygen atoms no longer pose any threat to the environment.

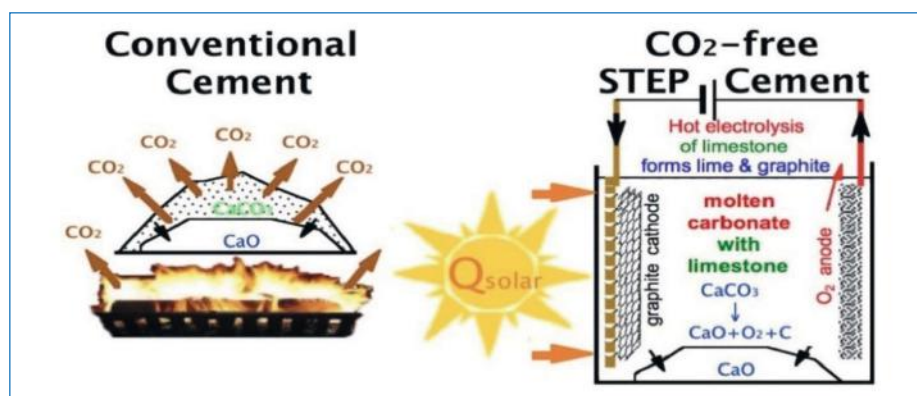


Fig. 5.29. The STEP cement process<sup>41</sup>

Lisa Zyga, Phys.org: Solar thermal process produces cement with no carbon dioxide emissions

The major cement producer CEMEX has begun work with the solar fuel start-up Synhelion to demonstrate the world's first zero-emission cement production process with high temperature (up to 1 500 °C) solar heat.

- Synthetic hydrocarbon fuels

In cement production processes, the use of synthetic hydrocarbon fuels is also a possible solution for reducing fuel consumption and  $\text{CO}_2$  emissions. The basis for producing synthetic hydrocarbon fuels is synthetic gas, or syngas, a gas mixture that contains varying amounts of  $\text{CO}$  and  $\text{H}_2$ . The  $\text{CO}$  in syngas could be produced from the sequestered  $\text{CO}_2$  emitted during cement production, and the  $\text{H}_2$  from excess of low-carbon electricity provided for example by wind and solar power. From the syngas, hydrocarbon fuels could be produced that allow the recycling of the sequestered original carbon in the cement production process once again. However, this type of cement manufacturing is still under research (Mikulčić et al., 2013c).

Yet, still recently, coal has been remaining an important fuel in some countries, such as China and India.

### 3.4. Low carbon cement

A variety of lower-carbon approaches are being pursued, with some already in practice, for example reducing the clinker factor. Drying Food Residue Biofuels (FRBs) to less than 15% moisture provides a stable, non-hazardous substitution in cement kilns and decreases the clinker level as mentioned previously.



Fig. 5.30. Advantages of LC3 Technology<sup>42</sup>

<sup>41</sup> [phys.org/news/2012-04-solar-thermal-cement-carbon-dioxide.html](https://phys.org/news/2012-04-solar-thermal-cement-carbon-dioxide.html)

<sup>42</sup> [lc3trcindia.com/strengths](https://lc3trcindia.com/strengths)

Most producers are already using Portland Limestone Cements (PLCs) and Supplementary Cementitious Materials (SCMs) in their cement to reduce emissions. Clay containing kaolinite can also be calcined to produce an effective SCM.

- Fly-ash-based geopolymers

This is a pozzolanic material with high alumina and silica content that provides a cementitious property in the presence of water. Using it provides an option to reduce the consumption of ordinary Portland cement (OPC), eliminate the disposal of fly ash in landfills, and decrease CO<sub>2</sub> emissions. Geopolymers (inorganic polymers) appear to be excellent low temperature binders; they are environmentally more acceptable than cement waste forms as the starting materials only need to be heated to about 700 °C instead of clinkering at 1 400–1 500 °C. Geopolymers have demonstrated excellent fire resistance and a smaller carbon dioxide footprint than that of traditional Portland cement. Fly ash, bottom ash and rice husk ash have been used as raw material for the production of geopolymers (chemical compositions such as silicon oxide (SiO<sub>2</sub>), aluminium oxide (Al<sub>2</sub>O<sub>3</sub>), calcium oxide (CaO), sodium oxide (Na<sub>2</sub>O), etc.). Geopolymers have significant effect on compressive strength.

For example, the Low-Carbon Technology Roadmap (LCTR) projections in the Indian cement industry shows a reduction of direct CO<sub>2</sub> emissions intensity to 0.35 tonnes of CO<sub>2</sub> per tonne of cement in 2050, about 45% lower than 2010 levels, thus saving between 212 and 367 million tonnes of CO<sub>2</sub> (MtCO<sub>2</sub>) by 2050 and attaining the Perform Achieve Trade (PAT) cycle targets. Other factors associated with fly ash should be taken into account:

- significant exposure to fly ash is a risk to human health and environment;
- large use of fly ash in making geopolymers can reduce CO<sub>2</sub> emissions and provide cost-benefits;
- NaOH, KOH, and Na<sub>2</sub>SiO<sub>3</sub> are the most used activators in fly-ash-based geopolymer cement;
- the durability of fly-ash-based geopolymers is mainly affected by the fineness of the fly ash particles;
- the long-term durability properties of fly-ash-based geopolymers provide them with great resistance to aggressive environments.

### 3.5. Carbon capture, utilisation and storage (CCUS)

Emissions in the cement industry are difficult to abate because they are produced from the calcination of limestone. The three traditional levers (fuel efficiency, alternate fuels and clinker substitution) will not meet the individual targets, even using new clinker to lower the need for heat in thermal reactions.

The present prognosis is that with the conventional levers employed for, the target (as in IEA-WBCSD-CSI) cannot be achieved without adopting Carbon Capture and Storage (CCS). The financial implications of adopting CCS are so adverse for the cement industry that it may turn out not to be viable. Under such circumstances, the economic feasibility of the carbon capture process is underpinned not by the price of CO<sub>2</sub> but by the sale of value-added products that could be and would be developed with sequestered CO<sub>2</sub>. This strategy thus justifies focusing on Carbon Capture and Use (CCU), instead of Carbon Capture and Storage (CCS). There is ongoing research on several technologies for utilising the captured CO<sub>2</sub> so as to boost the economic feasibility of CCU. Research has veered towards efficient carbon capture technologies and recycling methods that transform carbon into fuels and chemicals. Products such as methanol, urea or polymers could utilise 0.3-0.6 GtCO<sub>2</sub> a year in 2050, costing between USD 80 and USD 300 per tonne of CO<sub>2</sub>.

CO<sub>2</sub> fuels combine hydrogen with CO<sub>2</sub> to produce hydrocarbon fuels, including methanol, synthetic fuels and gas. Such CO<sub>2</sub> fuels could utilise 1 to 4.2 GtCO<sub>2</sub> a year in 2050, yet costs rise up to USD 670 per tonne of CO<sub>2</sub>.

In concrete building materials, CO<sub>2</sub> can be used to cure cement or to manufacture aggregates displacing conventional cement in the long run. The utilisation and storage of 0.1 to 1.4 GtCO<sub>2</sub> in 2050 is estimated to cost between USD 30 and USD 70 per tonne of CO<sub>2</sub>.

Bioenergy with carbon capture and storage: the operator captures CO<sub>2</sub> by growing trees, produces electricity through bioenergy and sequesters the resulting emissions with an estimated cost between USD 60 and USD 160 per tonne of CO<sub>2</sub>.

Soil carbon sequestration: Along with the storage of  $\text{CO}_2$  in soil, this enhances agricultural yield.

Carbon Capture and Storage (CCS) implies that:

- carbon from the ground should be returned to the ground;
- for process  $\text{CO}_2$  emissions, CCS technology is probably the only option to meet the carbon neutrality target;
- enhanced Oil / Gas Recovery (EOR/EGR) does not count as CCS.

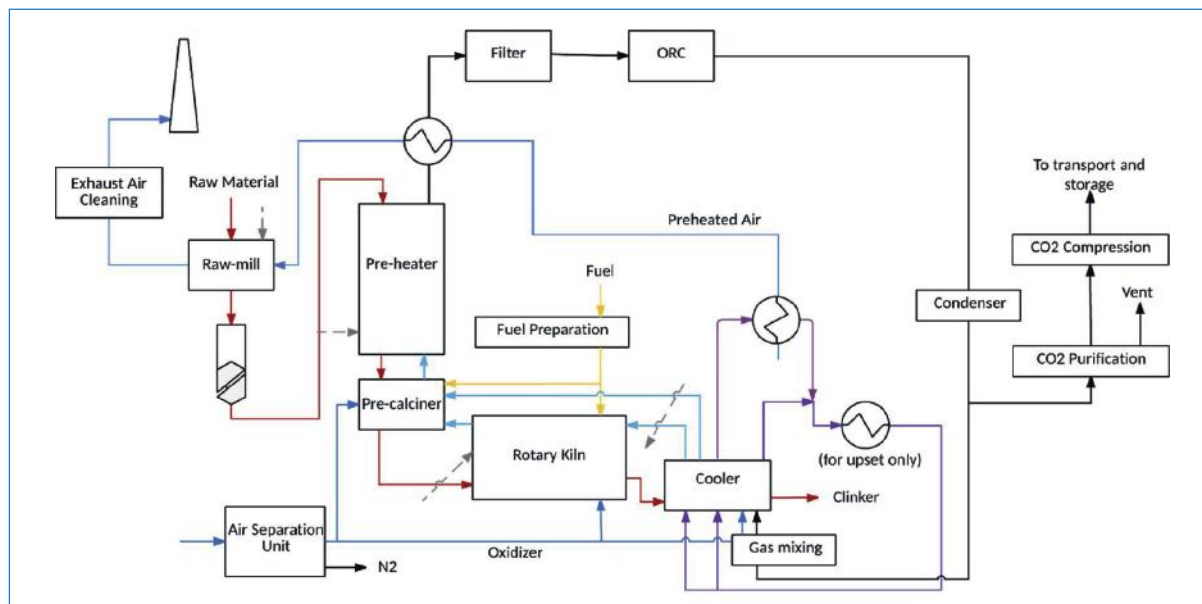


Fig. 5.31. Cement making in full oxy-fuel mode<sup>43</sup>

Mario Ditaranto, Jørn Bakken, Study of a full scale oxy-fuel cement rotary kiln, April 2019, International Journal of Greenhouse Gas Control 83:166-175, DOI:10.1016/j.ijggc.2019.02.008 License

Regarding the 'Capture' component of CCS, the three basic modes are oxy-fuel combustion, precombustion and post-combustion. Precombustion technologies are not beneficial for the cement industry as the major portion of  $\text{CO}_2$  comes from the processing of raw materials rather than from burning fuel; only post-combustion and indirect calcination are thus being considered.

**Carbon Capture and Facilitating Technologies:** post-combustion technologies may use a solvent, such as monoethanolamine (MEA) or amine scrubbing; or they may involve the post-combustion calcium looping cycle, which has been developed by the researchers working on the EU-funded CLEANKER project. Such technology aims to cut the  $\text{CO}_2$  emissions of cement plants by 90%. Calcium looping is a regenerative process that makes use of the ability of calcium-based sorbents to capture  $\text{CO}_2$  at high temperatures. In this process,  $\text{CO}_2$  is captured through the so-called carbonation of calcium oxide ( $\text{CaO}$ ) to form calcium carbonate ( $\text{CaCO}_3$ ).

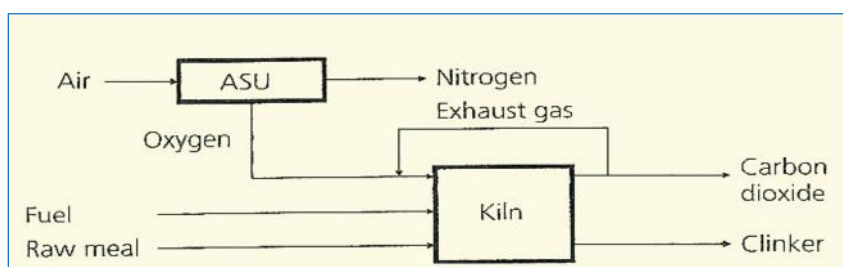


Fig. 5.32. The oxy-fuel combustion process

<sup>43</sup> [https://www.researchgate.net/figure/Cement-making-plant-in-full-oxy-fuel-mode-showing-process-components-gas-and-clinker\\_fig1\\_332123548](https://www.researchgate.net/figure/Cement-making-plant-in-full-oxy-fuel-mode-showing-process-components-gas-and-clinker_fig1_332123548)

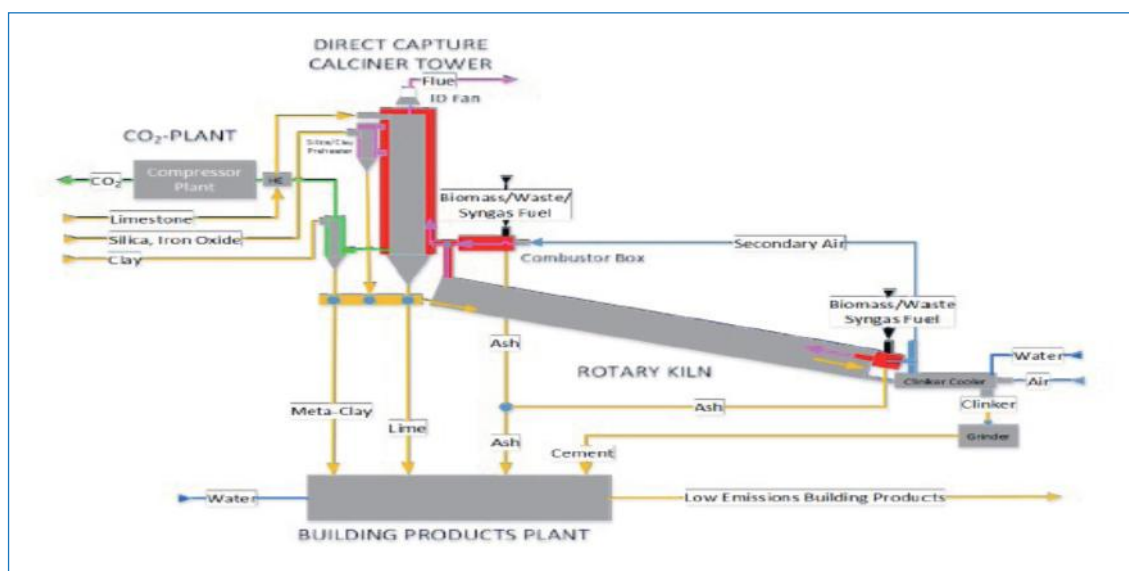


Fig. 5.33. Schematic flow sheet of the indirect calcination process with downstream option

Article "Veering Towards Carbon Capture and Transformation – An Emerging Technological Need for Carbon Dioxide Abatement Strategy" – by Dr Anjan K Chatterjee, Conmat Technologies Pvt Ltd, Kolkata, India.

The oxygen-enriched combustion and the oxy-fuel combustion are likely to be best-suited for new cement plants that would incorporate these design features. There is also a technological option of indirect calcination, which implies calcining the limestone or raw meal without any direct mixing with fuel combustion gases. This will also require specially designed processing equipment as depicted above, although no separation technologies, new materials or processes are involved.

The products derived from CCU would form a subset of novel low-energy low-carbon cements, which would obviously be non-Portland in character and manufactured through non-traditional processes. In this context, the major and widely shared concern is whether any of these new carbonated binding materials are realistic alternatives to Portland cements. Monitoring the availability and global distribution of the raw material resources, up-scaling of the manufacturing processes and extensive validation needed to confirm their fitness-for-purpose in the long run will solve this riddle. In the meantime, a new lever is therefore being examined globally to capture and recycle CO<sub>2</sub> (CCUS) as an industrial chemical. Aggregate production by the carbonation of kiln dust using Carbon 8 Technology and the carbonation of recycled concrete aggregates using cement flue gas, as in the FastCarb project is considered.

LafargeHolcim, as part of Austria's C2PAT initiative, which captures CO<sub>2</sub> and processes it with low-carbon-based hydrogen to produce hydrocarbon such as plastic or kerosene (CCUS), is also being examined.

Further carbon utilisation technologies and approaches have been proposed and tried, including:

- Carbon utilisation through Algae cultivation. The production of synthetic fuels is indeed regarded as an important development in energy vectors or energy stores. The production of biofuels through CO<sub>2</sub> stimulated growth of algae cultures has been the subject of much research. In the case of cement production, the kiln exhaust gases are utilised to grow the algae in bio-reactors. A large number of cement companies have undertaken pilot trials of bio-sequestration of CO<sub>2</sub> with algae.
- The electrochemical reduction of CO<sub>2</sub> to CO using metallic catalysts. The recent development of nano-sized porous silver catalysts with 92% selectivity is a direction towards viable commercial success. The organic fixation of carbon is another novel opportunity for development, which also merits attention.
- Other uses: CO<sub>2</sub> can and will be used in other industrial procedures. The use of CO<sub>2</sub> in the recarbonation of concrete and mineralisation of aggregates provides solutions for CO<sub>2</sub> emissions. Other uses of captured CO<sub>2</sub> contribute to reducing the consumption of fossil fuels.

### *CCUS Scenarios*

CCUS scenarios are based on the considerations that:

- the economic feasibility of CCUS is case dependent;
- cement plants emit more CO<sub>2</sub> than can be utilised;
- the economic benefits of using captured CO<sub>2</sub> are limited.

### *Research / Breakthrough on CCUS for cement industry*

**CCU:** 19 different research projects related to CCS and CCU are being developed globally, including one demonstration plant of about 0.5 million tonnes of CO<sub>2</sub> capture in Tamil Nadu, India. According to the Global CCS Institute (GCCSI), there are currently 19 large-scale projects in operation and 4 new projects under construction, with a total capacity close to 40 million tonnes of CO<sub>2</sub>.

Sebastián González and Flamant (2014) presented a hybrid cement production process that combines Concentrated Solar Thermal (CST) technology and the cement production process. Their study showed that by using CST for the calcination process in the cement production line, CO<sub>2</sub> emissions can be reduced by 40% since no fossil fuel would be used. The technical and economic assessment showed that it is indeed economically feasible to use concentrated solar thermal technology in the production process.

One of Japan's leading cement manufacturers, Tokuyama Corporation, is to initiate a 9-month long demonstration test programme of CO<sub>2</sub> capture technology for a cement plant. This is the first time the technology will be integrated with a cement plant.

Understanding the potential effects of hydrogen use on the cement production process and considering the geographic and cost viability of industrial clusters, are necessary steps towards its widespread utilisation. Cembureau, the European cement association, has already started a feasibility study into the effects of using hydrogen in a cement kiln.

Currently Heidelberg cement is also working with researchers at Swansea University to install and operate with green hydrogen.

Researchers at the Martin Luther University Halle-Wittenberg (MLU) in Germany and the Brazilian University of Pará have developed a climate-friendly alternative to conventional cement, without compromising performance. CO<sub>2</sub> emissions can be reduced during production by up to two thirds when overburden from bauxite (Belterra clay) deposits is used as a raw material.

**All in all**, no single technology will solve the huge problem of achieving the target of CO<sub>2</sub> emission reduction for the cement industry. A combination of appropriate technologies will be essential to make it financially viable and a concerted approach as part of a mission will have to be adopted while recognising the need to stay carbon neutral in the broader context of sustainability and competitiveness. Research studies have been conducted in various countries, as shown in *Table 5.5*.<sup>44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57</sup> below.

Technologies	1	Reduction of the clinker factor	Alternative fuel	Efficiency increase	Alternative fuel (20%): petroleum coke and coal to RDF, sewage, sludge, waste oil	Kiln heat efficiency	Electricity & thermal efficiency	Alternative fuel (biofuels)
	2	Alternative fuels	CCS	Raw material alternative		Grinding electrical efficiency	Alternative fuels	Energy efficiency
	3			Alternative fuel		Low carbon energy	Low clinker factor	New cement products
	4			Low carbon cement		Low carbon cement		Carbon dioxide uptake
	5					Low clinker factor		CCS/CCU

**Table 5.5.** A collection of research projects on potential combinations of technologies for reducing the CO<sub>2</sub> footprint of cement manufacturing processes

<sup>44</sup> Accelerating to zero by 2040! – Architecture 2030 (<https://architecture2030.org/accelerating-to-zero-by-2040/>)

<sup>45</sup> Ernest Orlando, Lawrence Berkeley National Laboratory China Energy Group, Energy Analysis Department Lynn Price, Ali Hasanbeigi, Hongyou Lu

<sup>46</sup> Best ways to cut carbon emissions from the cement industry explored – Imperial College London (<https://www.imperial.ac.uk/news/221654/best-ways-carbon-emissions-from-cement/>)

<sup>47</sup> Marta G. Plaza\*, Sergio Martínez and Fernando Rubiera CO<sub>2</sub> Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations MDPI

<sup>48</sup> CEMBUREU Position paper - Cembureau feedback to the European Commission's Public Consultation on Energy Efficiency Directive

<sup>49</sup> Thomas Schuiz Driving sustainable productivity FL Smidth

<sup>50</sup> Emission Reduction Approaches for the Cement Industry- AEEE.in Inside the Cement Industry: Challenges and Solutions

<sup>51</sup> Global Cement Industry's GHG Emissions — Global Efficiency Intelligence

<sup>52</sup> How Renewable Energy Could Support the Cement Industry's Energy Demand Kamlesh Jolapara

<sup>53</sup> Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers Laying the foundation for zero-carbon cement McKinsey & Company

<sup>54</sup> Low-Carbon Transition in the Cement Industry International Energy Agency

<sup>55</sup> Use of Alternative Materials in Cement Manufacturing Cement [Equipment.org](https://www.equipment.org)

<sup>56</sup> Hosam M. Saleh, Samir B. Eskander, Innovative cement-based materials for environmental protection and restoration [sciencedirect.com/topics/engineering/blended-cement](https://www.sciencedirect.com/topics/engineering/blended-cement)

<sup>57</sup> Zhi Cao, Eric Masanet, Anupam Tiwari, Sahil Akolawala Climate works foundation Industrial Sustainability Analysis Lab - Deep decarbonisation pathways for the cement and concrete cycle in the United States, India, and China

## 4. Decarbonisation policy

In order to achieve the carbon neutrality goal for the global cement industry, key stakeholders, including international and national industry associations and cement producers themselves, need to cooperate to develop a general policy framework.

### 4.1. Existing carbon reduction policies

Methods of policy implementation usually vary according to economic environments; the policies of major cement-producing countries are listed in *Table 5.6*.

Country	Development background and current situation	Major Carbon Reduction Policies	Highlights
Germany	<p>The cement industry in Germany started in 1877, and many of its technologies and equipment are at the forefront of the world. These include the development and application of flue gas denitrification and alternative fuels, as well as the kilns, burners, and grinding equipment in use.</p> <p>The integrated cement capacity of Germany is 32 million t/yr, accounting for about 0.75% of global cement production. Flue gas denitrification and alternative fuel technologies, as well as production equipment, are at the forefront of the world. This has a relatively long history and had remarkable results in the application of inferior fuel oil, petroleum coke and alternative fuels. The fuel substitution rate increased from 4.1% in 1987 to 68.3% in 2017. Current alternative fuel types include RDF, SDF, and sub-coal<sup>58</sup>.</p>	<ol style="list-style-type: none"> <li>1. Solid Waste Framework Directive (Directive 2008/98/EC)</li> <li>2. Industrial Pollutant Emissions Directive (2010/75/EU)</li> <li>3. Waste Shipment Regulation (1013/2006/EC)</li> </ol>	<ol style="list-style-type: none"> <li>1. The Framework Directive is EU's basic legal framework on waste disposal. The Directive reflects the concept of sustainable waste management and seeks to implement fundamental principles of modern waste management, such as stopping the generation of waste and facilitating the recycling and reuse of waste and energy. It provides for the safe disposal of waste, for disposal equipment, and for clear guidelines for the disposal of waste end-products (EOW) and for the manufacturing of products which must meet environmental standards for the waste and not be damaging to human health.</li> <li>2. The Directive is the main tool for regulating pollutant emissions from industrial installations in the EU. As it relates to the environmental impact of many activities, such activities require prior review and (as the case may be) specific conditions may be imposed.</li> <li>3. The regulation implements control measures for the transport of waste within, to and from the EU. It also sets out procedures for the transport of waste according to the destination of the goods, the type of waste and the treatment of waste after shipment.</li> </ol>
Japan	<p>Cement production in Japan peaked in the 1990s at nearly 100 million t/yr and is now down to 50 million t/yr. Japanese cement plants played a great role in waste disposal, resource recycling and circular economy.</p>	<ol style="list-style-type: none"> <li>1. Carbon recycling and materials industry growth strategy in line with carbon-neutral Green Growth Strategy for 2050</li> <li>2. "Innovative Environmental Innovation Strategy"</li> </ol>	<ol style="list-style-type: none"> <li>1. Establishes the large-scale recycling of carbon dioxide technology in domestic cement plants as a target for the future development of the cement industry, and promotes the development and demonstration application of carbon dioxide curing technology, using various calcium sources, such as waste.</li> <li>2. Proposes the development of a new technology to produce new types of cement from carbon dioxide (carbon dioxide recycling in cement production), which is currently in the development stage.</li> </ol>
Croatia	<p>There are three cement producers in Croatia. Annual production is about 3.9 million tonnes of cement with an average clinker factor of 0.77. The main fuels are petroleum coke and coal, with alternative fuels including RDF, sewage sludge and waste oil. The utilisation rate of alternative fuels is about 20%.</p>	<ol style="list-style-type: none"> <li>1. Green Certificates</li> <li>2. Legislation for handling Construction waste material</li> <li>3. EU Green Deal</li> <li>4. EU Emissions Trading System (EU ETS)</li> </ol>	<ol style="list-style-type: none"> <li>1. Green Certificates are officially known as Renewable Energy Certificates (RECs).</li> <li>2. Under Croatian and EU legislation, construction waste materials are defined as special waste that needs to be handled according to a specific procedure, which leads such waste to being reused in the road construction industry.</li> <li>3. The European Green Deal is a set of policy initiatives by the European Union. An impact-assessed plan will also be presented to increase the EU's GHG emission reductions target for 2030, of at least 50% and aiming at 55% compared with 1990 levels.</li> <li>4. EU ETS is the core principle of the "Carbon Trading Mechanism" under the Kyoto Protocol.</li> </ol>

<sup>58</sup> A look at the history of German cement industry to explore the progress of alternative fuel technology in cement kilns, Jiang Xuchang, China cement, 2020.12

China	China ranks first in the world in annual cement production. The energy source is mainly coal. The equipment and technological development of the cement industry is relatively advanced, and China leads the world in waste heat power generation technology. The current clinker coefficient is about 0.66.	<ol style="list-style-type: none"> <li>1. Capacity restriction policies.</li> <li>2. Accelerating the development of mandatory standards for the cement industry</li> <li>3. CO<sub>2</sub> assessment</li> <li>4. Organising to build “six-zero” model factories in the building materials industry</li> </ol>	<ol style="list-style-type: none"> <li>1. Includes the elimination of outdated production capacity, capacity reduction and replacement, limited peak production and strict control of new production capacity.</li> <li>2. Specific policies and standards include: Unit consumption quotas for cement products, limits on energy consumption in cement production, guidelines for comprehensive solid waste recycling, and increased monitoring and use of hazardous waste management programmes.</li> <li>3. At present, only the power industry in China has fully entered the carbon market, while all other industrial sectors have not. The cement industry’s carbon accounting work is to prepare for entering the carbon market and promoting carbon emission reduction in production enterprises.</li> <li>4. The “six-zero” demonstration plant refers to zero purchased electricity plant, zero fossil energy plant, zero primary resource plant, zero carbon emission plant, zero waste plant and zero employee plant. This aims to push the industry to achieve green, low-carbon, safe and high-quality development.</li> </ol>
Argentina	Argentina produces about 11.08 million tonnes of cement per year with a clinker factor of about 0.7. Energy sources are mainly natural gas and petroleum coke. Alternative fuels include solid waste and biomass fuels.	<ol style="list-style-type: none"> <li>1. Carbon tax on fossil fuels</li> <li>2. Indicator requirements for alternative fuels, raw materials, and waste recycling</li> </ol>	<ol style="list-style-type: none"> <li>1. The CO<sub>2</sub> tax on fuels is about USD 5 per tonne of coke.</li> <li>2. The hazardous waste generated is about 0.06 kg/ t cement; the recovered rate is 69.3%; the non-hazardous waste generated is about 0.49 kg/t cement; the recovered rate is 50.4%.</li> </ol>
Switzerland	Switzerland produces about 3 million tonnes cement per year. Energy sources are mainly fossil-based. Switzerland is rich in cement raw materials (limestone and marl), but the mining of raw materials is restricted for some producers, due to land use, opposition to expanded mining, etc	<ol style="list-style-type: none"> <li>1. The Swiss Energy Strategy 2050</li> <li>2. Long-term climate strategy to 2050</li> <li>3. Carbon tax</li> </ol>	<ol style="list-style-type: none"> <li>1. The Swiss Energy Strategy 2050 aims to improve energy efficiency, reduce energy consumption, encourage renewable energy use, etc. For the building sector, measures to improve the buildings’ energy efficiency are included (e.g. subsidies for the cost of energy-efficient building retrofits, tax incentives for building retrofits, and support for the insulation and replacement of heating systems).</li> <li>2. The long-term climate strategy shows it can reduce GHG emissions by 2050 by around 90% of the 1990 level. The remaining emissions must be balanced with NETs (negative emissions technologies). It formulates ten basic strategic principles and proposes emission pathways for the buildings, industry, transport, etc.</li> <li>3. Since 2008 Switzerland has a CO<sub>2</sub> levy which has been increasing from CHF 12 /tonne in 2008 to nearly CHF 100 now.</li> </ol>

India	<p>India ranks second in the world in cement production. About 294 million tonnes of cement will be produced in fiscal year 2021. Fuel primarily comes from fossil energy. The cement demand mix is 65%-70% for real estate, 20%-23% for infrastructure, and 10% for the remaining commercial and industrial buildings.</p>	<ol style="list-style-type: none"> <li>1. National Action Plan for Climate Change (NAPCC)</li> <li>2. Coprocessing of hazardous waste</li> <li>3. The Bureau of Energy Efficiency (BEE)</li> <li>4. CII Energy benchmarking manual</li> <li>5. BEE &amp; UNIDO</li> <li>6. Clean Development Mechanism (CDM)</li> <li>7. Mission Innovation (MI)</li> </ol>	<ol style="list-style-type: none"> <li>1. The National Action Plan on Climate Change (NAPCC) aims to stop the accelerating warming of India by focusing on renewable energy. The 9th mission of the NAPCC aims at reducing the large amount of CO<sub>2</sub> emissions from coal-fired power plants.</li> <li>2. The coprocessing of hazardous waste in the cement industries has been encouraged, with appropriate, environmentally-safe methods.</li> <li>3. The Bureau of Energy Efficiency (BEE) included 478 units from eight energy-intensive sectors, including cement. The minimum annual energy consumption of each DC (Designated Consumers) was 30 000 tonnes of oil equivalent (toe).</li> <li>4. CII (Confederation of Indian Industry) has published an energy benchmarking manual that has been recognised as a useful tool for performance assessment, energy efficiency improvement and target-setting across the industry to help cement plants achieve the status of efficient role model units.</li> <li>5. BEE and the United Nations Industrial Development Organization (UNIDO) launched a five-year programme that aims to promote innovative low-carbon technologies among the industry and other sectors of the Indian economy.</li> <li>6. The Clean Development Mechanism (CDM) is a flexible compliance mechanism introduced in the Kyoto Protocol at the third Conference of the Parties (COP3) to the UN Framework Convention on Climate Change (UNFCCC). As part of the project, saving fossil fuel from Waste Heat Recovery System (WHRS) was included in the CDM of the UNFCCC.</li> <li>7. The Accelerating CCUS Technology (ACT) initiative under the Mission of Innovation (MI) aims to facilitate technology exchange within the industry and optimise the allocation of R&amp;D funds. It also seeks to bring India's focus back to CCS/CCUS.</li> </ol>
United States of America	<p>The US cement production ranks among the top five in the world. 89 million tonnes of cement were produced in 2020. The development of the cement industry has been constrained in recent years by enterprise closures, production shutdowns, overcapacity, plant upgrades, low-priced imported cement and the COVID-19 pandemic.</p>	<ol style="list-style-type: none"> <li>1. Carbon tax credits</li> <li>2. Dedicated funding for carbon removal technology development</li> <li>3. Industrial Sector Decarbonisation Programme</li> </ol>	<ol style="list-style-type: none"> <li>1. Carbon tax credits serve as an incentive for using decarbonisation technology, such as CCUS.</li> <li>2. The first funding, in the amount of USD 60 million, was provided by House and Senate appropriators.</li> <li>3. Includes: USD 10 billion investment to accelerate clean hydrogen development; launch of the "Buy Clean" procurement to promote the use of building materials with lower hidden emissions and pollutants; use of trade policies to incentivise clean manufacturing; release of the Council on Environmental Quality CCUS guidelines; and an interdisciplinary industrial decarbonisation research initiative.</li> </ol>
South Africa	<p>The annual cement production in South Africa is about 22 million tonnes. The source of energy is mainly coal. Electricity is principally from coal-fired power generation. Alternative fuels mostly include waste tires and fly ash from coal-fired power generation. Fly ash production is about 30 million t/yr. The clinker substitution rate for South Africa approximates 41% and will continue to increase in the future.</p>	<ol style="list-style-type: none"> <li>1. Carbon tax</li> <li>2. South Africa National Accreditation System (SANAS): Accreditation programme (ISO 14065)</li> <li>3. South Africa National Treasury (SANT)</li> </ol>	<ol style="list-style-type: none"> <li>1. Carbon taxes have been implemented. However, the cement market in South Africa still needs more regulations for fair competition to be achieved.</li> <li>2. According to the requirements of ISO 14065, SANAS has indicated how to validate GHG emissions and set a corresponding verification organisation. These requirements will be complied with in the writing of mandatory GHG reports and the evaluation of the implications of the carbon tax.</li> <li>3. South Africa National Treasury (SANT) promotes the use of locally produced clinker and sourced secondary materials. It also encourages the local cement industry to consider modifying plants to reduce GHG emissions.</li> </ol>

**Table 5.6.** Existing carbon reduction policies in major cement producing countries

## 4.2. Policy recommendations

International research institutions, including the Global Cement and Concrete Association (GCCA), the International Energy Agency (IEA), the Cement Sustainability Initiative (CSI), national industry associations, and major cement producers have recently published technical roadmaps for low-carbon development in the cement industry. As countries have different energy and resource endowments, the current situations and problems cement producers face are different, and the policy orientations for carbon emission reduction also differ. Policy recommendations for the development of the cement industry are presented here, considering the development of existing low-carbon emission reduction technologies and innovative low-carbon technologies, with a view to providing stronger policy support for the implementation of these production technologies in the cement industry. Some recommendations are going far beyond the cement sector.

### 4.2.1. Supportive policies for carbon reduction technologies

- Accelerate the adoption and application of technologies for the improvement of energy efficiency. First, governments should make sure that cement industry associations set and implement energy efficiency requirements and CO<sub>2</sub> emission standards for the cement industry. Governments and relevant authorities should then set energy efficiency improvement targets and formulate corresponding action plans according to the targets, such as reducing electricity consumption per unit product of the grinding system. This can be achieved by pushing for the installation of such systems as high-efficiency grinding and vertical coal mills, and encouraging cement producers to use energy-efficient motors to improve production efficiency. In addition, fiscal incentives that reward clean energy investments should be implemented. Increasing the use and production of low-carbon energy and recovering waste heat can be rewarded; on the other hand, plants with inefficient capacity can be penalised by reductions in subsidies.
- Encourage the increased use of alternative raw material / fuel / energy

First of all, governments can work with industry authorities to promote policies and regulations that prohibit or severely restrict landfills, as well as the use of dedicated incineration units for waste treatment, and allow waste collection and the treatment of alternative fuel<sup>59</sup>.

Moreover, regulations for the management of waste recycling management can be developed and strengthened. These may include the separate collection and treatment of industrial, domestic and hazardous waste, and establishment of corresponding recycling and treatment facilities and markets (Industrial and hazardous waste, including, for example, steel slag, slag, fly ash, and calcium carbide slag). For example, the EU governments have established a comprehensive sorting and recycling system to enable cement producers to handle RDF according to its different properties<sup>60</sup>. However, with the future implementation of carbon reduction measures in many industrial sectors, the amount of waste collected will gradually decrease, thus affecting future alternative applications in the cement industry. Governments can implement technical specifications for cement kiln co-disposal and develop industrial waste management. Furthermore biomass fuel is also being used as an alternative fuel by some producers. In the future, a more level playing field could be provided for the use of biomass waste, in terms of reducing carbon emissions and related carbon-pricing mechanisms, by eliminating subsidies targeting only specific industries<sup>61</sup>.

In addition, government and cement industry authorities should develop and strengthen guidelines for the use of alternative raw materials and fuel including concentrated solar power for clinker production and ensure that producers follow proper procedures based on those guidelines. Moreover, the development of fiscal incentives for the use of alternative fuels for power generation and taxation, and the related regulatory framework, must be completed.

<sup>59</sup> IEA(2018),Technology Roadmap-Low Carbon Transition in the Cement Industry, (<https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry>)

<sup>60</sup> Cementing the European Green Deal, the European Cement Association

<sup>61</sup> Cembureau's Building carbon neutrality in Europe, the European Cement Association

Finally, governments and cement industry authorities should develop and promote the best international guidelines for alternative fuel use. The relevant authorities must also then ensure that producers provide adequate quality control protocols in terms of alternative material availability and impact monitoring. Assistance in processing alternative fuel use permits must also be available.

- Clinker substitution

Governments and cement industry authorities can improve the availability of replacement clinker through the development of recycling policies and provide R&D funding for the development of processing technologies and performance tests for clinker replacement. The regional availability of clinker substitution is largely influenced by local environmental policies and laws. For example, the availability profile of fly ash is limited by future carbon reductions in the power sector; coal-fired power generation uses denitrification technology to reduce nitrogen oxide emissions, but the resulting higher ammonia concentrations in fly ash is not suitable as clinker replacement.

To increase the use of low clinker cement in public procurement policies, the prerequisites for use are technical feasibility, availability of clinker substitutes, and carbon footprint analysis using a life-cycle approach<sup>62</sup>.

Governments can develop appropriate public procurement policies that reduce the preference for high clinker content cements. They can also work together with industry associations to develop new national product standards and specifications, or revise existing ones, to allow more blended cements to be more widely used. For example, standards can be developed based on cement properties rather than composition. It must then be ensured that local agencies recognise such standards.

Finally, measures can be taken to stimulate the long-distance transport of blended materials such as fly ash and granulated blast furnace slag.

- New low-carbon cement

New low-carbon cements include the use of alkaline excitors to excite industrial slags so as to prepare new gel materials, limestone calcined clay cements (LC3), and the replacement of cement clinker with supplementary cementitious materials (SCM).

Governments can make sure that cement industry associations develop public procurement policies for the promotion of new low-carbon cements. New cement standards, or revisions to existing ones, can take into consideration the use of new low-carbon cements. These standards should not only specify chemical composition but also include indicators such as performance requirements.

In terms of capital, financial institutions can provide support towards research and development of new low-carbon cement technologies. Finally, international training activities by industry associations and research institutions can encourage national standardisation and certification associations to initiate exchange of experiences in new cement R&D technologies.

- Innovative low-carbon technologies

Innovative low-carbon technologies mainly refer to carbon capture, utilisation and storage (CCUS), and other low-carbon technologies that provide technical support for the implementation and application of CCUS, such as oxygen-rich or oxyfuel combustion.

Governments and cement industry authorities should work together with other industry associations to develop policies and legislation related to carbon capture or utilisation.

As part of broader climate change strategies, governments can provide financial support for R&D and pilot projects on carbon capture and utilisation technologies. Appropriate policies which incentivise the development of these low-carbon technologies must also be available.

Collaboration between the cement industry and other energy-intensive industries, such as the steel industry, should also be encouraged. Both, for example, can benefit from converting captured CO<sub>2</sub> into fuel and other applications using synthetic technologies from the chemical industry.

---

<sup>62</sup> Cembureau's Building carbon neutrality in Europe, the European Cement Association

New market mechanisms can be created to replace the previous Clean Development Mechanism (CDM). This will in turn provide financial support for carbon capture and use projects, as well as facilitate loans for carbon capture projects and the creation of emission trading schemes, such as the EU ETS.

National governments can coordinate the regulatory framework for CCS/CCU internationally, support the coordination and demonstration of CO<sub>2</sub> transport networks at regional, national, and international levels, and optimise the development of infrastructure.

Governments and industry authorities should promote international cooperation to develop an internationally harmonised regulatory framework, such as through the United Nations Framework Convention on Climate Change (UNFCCC) to harmonise approaches to the safe siting, operation, maintenance, monitoring, and verification of CO<sub>2</sub> permanent storage<sup>63</sup>. Finally, authorities can work with the industry to educate and raise awareness of these low-carbon technologies, which will increase social acceptance.

#### 4.2.2. Carbon market mechanisms

- The Cement industry within the carbon market

At the International level, it is recommended to establish a unified and appropriate global carbon pricing system in order to create a level playing field in terms of carbon costs, avoid carbon leakage and ensure a managed transition to a net-zero economy<sup>64</sup>.

Cooperation between the cement industry and the financial sector must be strengthened. To this end, the standard system and information disclosure mechanism, which supports green finance, should be improved. A cooperative change policy for low-carbon development in the cement industry must also take place.

- Cement industries without access to the carbon market

For the cement industries that have not entered the carbon market, it is recommended to prepare in terms of the following aspects:

- the government and relevant departments must develop and improve the legal system of carbon trading and further promote the construction of the carbon market;
- research institutions should unify carbon emission and carbon trading data from the national level and clarify the national rules for the allocation of emission rights;
- relevant departments need to develop accounting standards and methods for the carbon emissions of industry enterprises;
- financial institutions must establish a carbon emission financing market and enrich financing tools.
- Governments are responsible for determining carbon pricing mechanisms, including emission trading systems and carbon taxes.

#### 4.2.3. Environmental Protection Policies

- Emission standards

Cement industry authorities need to work together with environmental protection departments to develop or revise original pollutant emission standards, and push cement producers to adopt production technologies with low environmental impact.

- Emission regulation

Environmental protection departments can propose rules for monitoring data identification for cement producers and establish a system of rules for determining data validity.

Governments and industry authorities should propose technical specifications for pollution control as a result of cement production, and specify pollutant control and monitoring requirements. Governments can also propose corresponding comprehensive air pollution control programmes according to local air environment and implement production restrictions, production suspensions and remediation methods as necessary<sup>65</sup>.

<sup>63</sup> Cembureau's Building carbon neutrality in Europe, the European Cement Association

<sup>64</sup> PCA(2021), Roadmap to carbon neutrality

<sup>65</sup> e.g. for decarbonizing concrete

## 5. Pathway to net-zero CO<sub>2</sub> emission

This fifth section proposes a carbon neutral pathway to the future development of the cement industry, based on low-carbon technologies that can be adopted by the industry and carbon reduction policies that have been proposed on the current development status of the global cement industry.

### 5.1. Carbon reduction potential of decarbonisation technologies

#### 5.1.1. Energy efficiency improvement

Improving energy efficiency has been widely considered for decarbonisation. As the adaptation of energy saving technologies is different for each country, potentials for energy efficiency improvements vary. For China, it is considered as 6-10 kg CO<sub>2</sub>/tonne clinker. According to the scenario analysis conducted by China National Building Material (CNBM), the baseline scenario is 0.8695 tonne CO<sub>2</sub>/tonne clinker for a cement clinker emission intensity without any technical emission reduction factor; the emission reduction scenario is 0.8432 tonnes CO<sub>2</sub>/tonne clinker by 2060 for a cement clinker emission intensity with technical conditions improving energy efficiency.

#### 5.1.2. Alternative raw material

The potential of alternative raw materials is 4-7 kg CO<sub>2</sub>/tonne clinker. According to the CNBM scenario analysis, the cement clinker emission intensity in the baseline scenario is 0.8695 tonne CO<sub>2</sub>/t clinker for China. The abatement scenario involves using alternative raw material technologies, and results in a cement clinker emission intensity of 0.8369 tonne CO<sub>2</sub>/t clinker by 2060. For CEMBUREAU, the use of decarbonated raw material is expected to result in a 3.5% reduction of process CO<sub>2</sub> by 2030 and up to 8% by 2050<sup>66</sup>.

#### 5.1.3. Alternative fuel

The increasing use of alternative fuel, combined with the use of electrical heating and hydrogen is expected to result in near-zero CO<sub>2</sub> emissions from fuel. For China, the emission reduction potential of alternative fuels is 140-285 kg CO<sub>2</sub>/t clinker. For CEMBUREAU, hundreds of kilograms of CO<sub>2</sub> are planned to decrease through fuel substitution<sup>66</sup>. And for the Portland Cement Association (PCA), the alternative fuels could make up to 50% of the industry's fuel mix, with no more than 10% coal and petcock use by 2050<sup>67</sup>.

#### 5.1.4. Low carbon cement

The emission reduction potential for low carbon cement development is 40-70 kg CO<sub>2</sub>/tonne clinker. Low carbon cement technologies include two categories: new clinker systems and clinker factor reduction. New clinker system cement includes high berylite cement, sulphur (iron) aluminat cement, high berylite sulphoaluminate cement, calcium carbonate silicate cement, etc. Compared with ordinary silicate cement, the carbon emission intensity per unit of cement clinker is much lower.

#### 5.1.5. CCUS

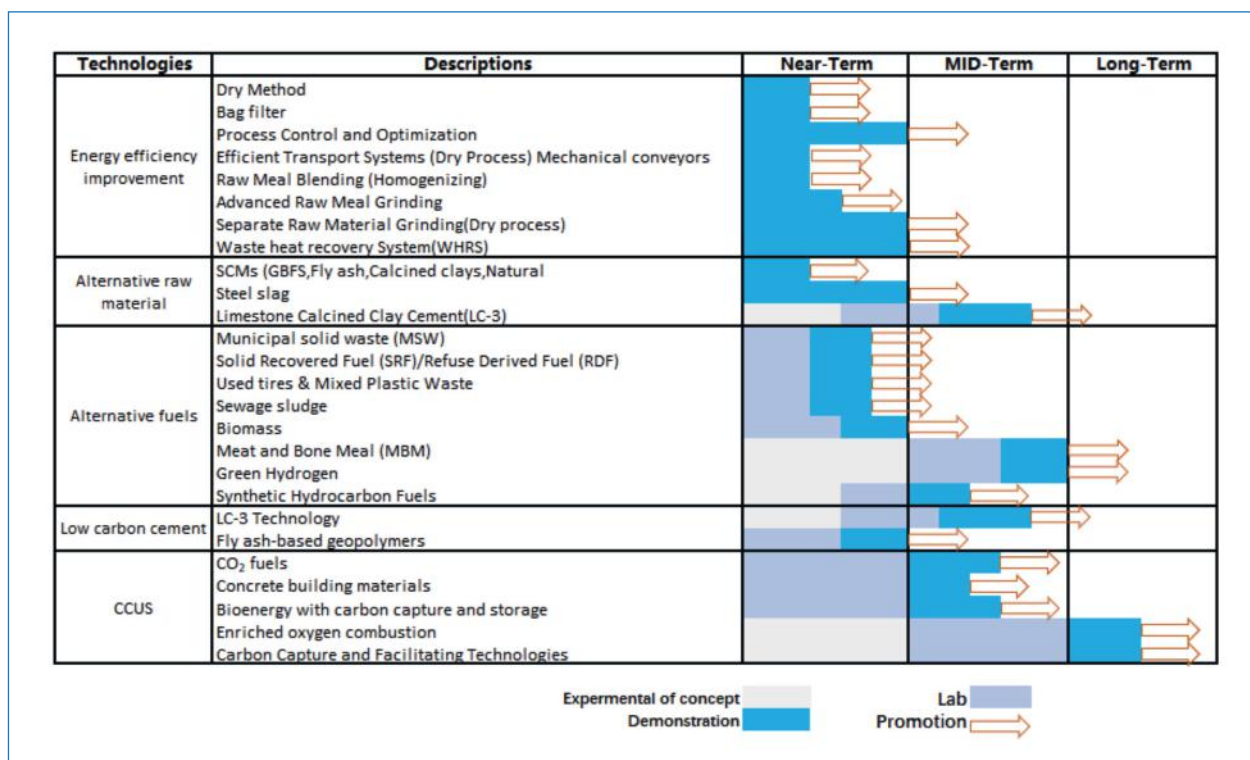
CCUS has an emission reduction potential of 200-400 kg CO<sub>2</sub>/tonne clinker, and it might be the only technical pathway to achieving near-zero emissions in the cement industry. In view of the decisive role of CCUS technology in a carbon neutral cement industry, CCUS technology will have to be promoted on a large scale.

<sup>66</sup> 5C Carbon Neutral Roadmap of Cembureau, European Cement Association

<sup>67</sup> PCA(2021), Roadmap to Carbon Neutrality

## 5.2. Pathway to net-zero CO<sub>2</sub> emission

The pathway to net-zero CO<sub>2</sub> emission for the cement industry is shown in *Table 5.7*.



*Table 5.7.* Preliminary technology development pathway

## 6. Case studies

Many production companies have been carrying out research and industrial demonstrations of low carbon technologies for the cement industry. Some typical cases used for analysis and evaluation are shown in *Table 5.8*.

Countries	Argentina	Canada	China	Croatia	India	South Africa	Sweden
Case Studies	<ol style="list-style-type: none"> <li>1. Reduction of CO<sub>2</sub> intensity in the fuel mix</li> <li>2. Low clinker factor</li> <li>3. Calcined clays is used as artificial pozzolana</li> </ol>	<ol style="list-style-type: none"> <li>1. LaFargeHolcim: CCS (Svante Pressure Swing Absorption)</li> <li>2. LaFarge: alternative fuel</li> </ol>	<ol style="list-style-type: none"> <li>1. CONCH: CCUS (dry ice)</li> <li>2. CCUS (oil displacement or landfilling)</li> </ol>	<ol style="list-style-type: none"> <li>1. NEXE: alternative fuel (100%, petroleum coke and coal to RDF, sewage, waste oil)</li> </ol>	<ol style="list-style-type: none"> <li>1. Dalmia: CCUS (CDRMax)</li> <li>2. ACC: Coprocessing of plastic waste</li> <li>3. JK Lakshmi: Waste heat recovery</li> </ol>	<ol style="list-style-type: none"> <li>1. Concrete: reduce the cement content and use water reducing</li> </ol>	<ol style="list-style-type: none"> <li>1. Cementa: CCS</li> <li>2. Cementa &amp; Vattenfall (CemZero): electrification/ biomass/CCS</li> </ol>

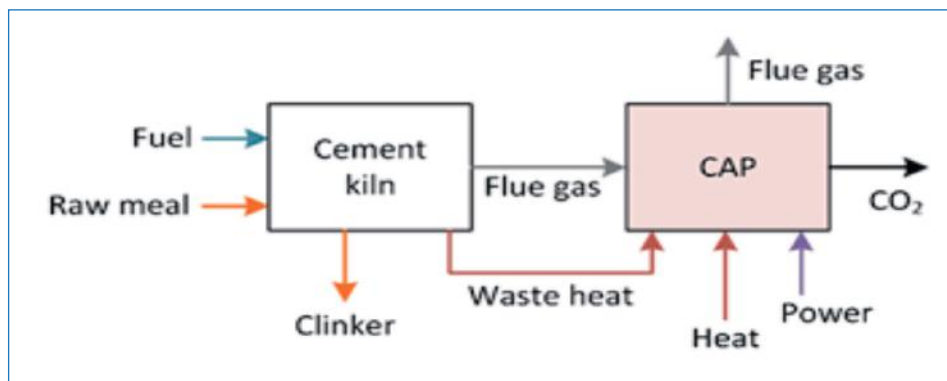
*Table 5.8.* Typical case studies in some countries

### 6.1. Dalmia cement of India

Indian industries are leading some of the largest projects exploring the role of CCUS, which is being recognised by the industries, but more stakeholders are needed for such a transition, in order to promote the adoption of CCS/CCUS technology in India.

Dalmia Cement, with the aim of dropping its emission level to 30 kg CO<sub>2</sub>/tonne by 2040, has announced the installation of a large-scale CCUS facility with 0.5 Mt CO<sub>2</sub> capacity per annum at one of its plants in Tamil Nadu, India. For the implementation of this facility, Dalmia Cement and Carbon Clean Solutions, UK, have partnered

to adopt Carbon Clean Solutions' patented technology, CDRMax (Global CCS Institute 2019). This technology is far from becoming mainstream.



**Fig. 5.34.** Diagrammatic sketch of Dalmia cement  
CAP: CO<sub>2</sub> Capture unit

## 6.2. Brevik carbon capture and storage project

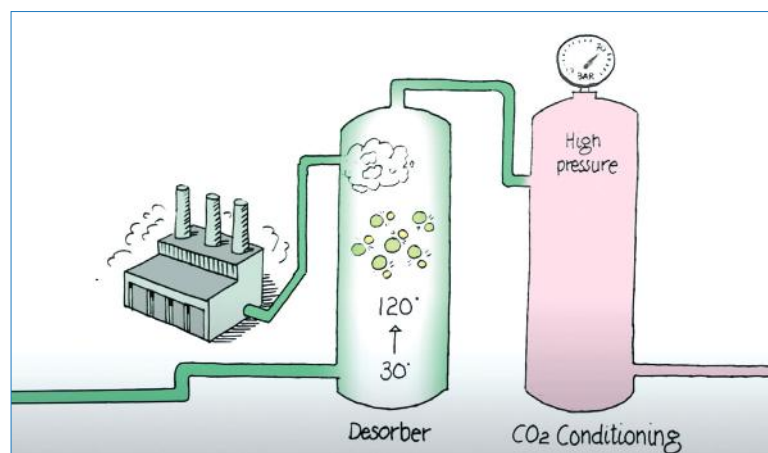
The Norwegian government had shortlisted Brevik for an industrial-scale CO<sub>2</sub> capture trial at the beginning of 2018. In September 2019, a memorandum of understanding on the capture and storage of CO<sub>2</sub> was signed between Heidelberg Cement and the state-owned Norwegian energy Group Equinor.

Heidelberg Cement has committed itself to reducing its specific net CO<sub>2</sub> emissions per tonne of cementitious material from 750 kg in 1990 to 525 kg in 2025, i.e. by more than 30%.

The Brevik carbon capture and storage (CCS) project will enable the capture of 400 000 tonnes of CO<sub>2</sub> per year and transportation for permanent storage, making it the first industrial-scale CCS project at a cement production plant in the world. *Fig. 5.35.* is a brief introduction of the process. Work on the new facility in Brevik is expected to begin immediately, with the goal of starting CO<sub>2</sub> separation from the cement production process by 2024. The end result will be a 50% cut of emissions from the cement produced at the plant.

Heidelberg Cement focuses on three technologies for CO<sub>2</sub> capture:

- post-combustion capture
- oxyfuel
- direct separation.



**Fig. 5.35.** Diagrammatic sketch of CO<sub>2</sub> capture

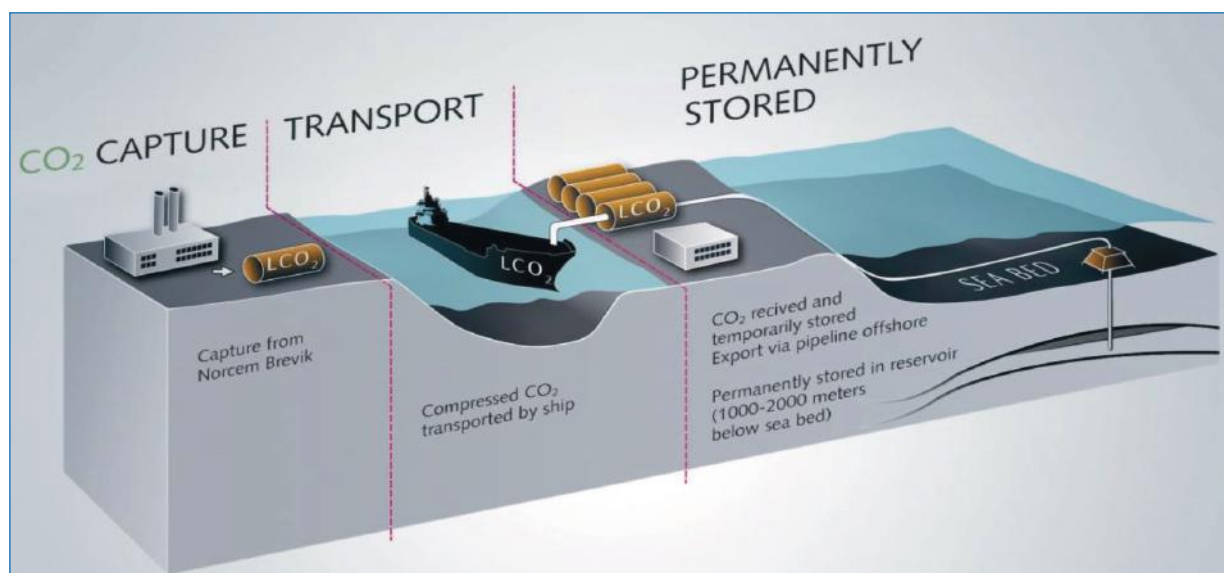


Fig. 5.36. Diagrammatic sketch of CCS in Heidelberg Cement  
The Brevik CCS project

<https://www.heidelbergmaterials.com/en/carbon-capture-and-storage-ccs>

### 6.3. Low Emissions Intensity Lime And Cement (LEILAC) projects

The Low Emissions Intensity Lime And Cement (LEILAC) projects will seek to prove a new type of carbon capture technology called Direct Separation. Such technology provides a common platform for CCUS in both the cement and lime industries, and seeks to tighten emissions standards for CO<sub>2</sub> emission reductions and CO<sub>2</sub> capture.

The LEILAC1 project has developed, built and now operates a pilot plant at the Heidelberg Cement plant in Lixhe, Belgium to demonstrate the uniqueness of such technology as it aims to enable the capture of CO<sub>2</sub> emissions from the cement and lime industries without significant energy or capital penalty other than compressing the CO<sub>2</sub>.

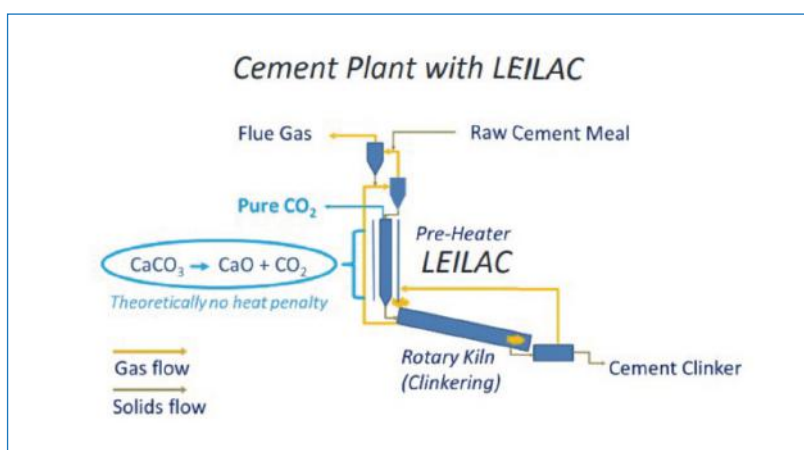


Fig. 5.37. Diagrammatic sketch of LEILAC

PowerPoint Presentation: Leilac 2 – Scaling Up Low-Carbon Solutions October 2021, Slide 4

<https://act-anica.eu/wp-content/uploads/2021/10/Thomsen-Calix.pdf>

The LEILAC pilot is designed to run up to 240 t/day throughput, carry out fundamental research on the process demands and performance, and demonstrate that such technology works robustly to begin scale-up planning.

The LEILAC2 project aims to scale-up the Direct Separation technology developed and tested in LEILAC1 and to build a demonstration plant that will separate 20% of the process emissions of a regular cement plant, i.e. around 100 000 tonnes of CO<sub>2</sub> per year.

#### 6.4. LafargeHolcim cement plant

The LafargeHolcim cement plant in Vancouver, Canada, has demonstrated the use of pressure-swing absorption (PSA) technology to capture CO<sub>2</sub> at pilot scale. The company has called this plant the 'CO<sub>2</sub> MENT' demonstration project. In order to further reduce emissions, it also plans to use lower carbon fuels, rather than fossil fuel to power the plant. This demonstration project has now accumulated more than 1 000 hours of operation while achieving an 85% recovery of total CO<sub>2</sub> emissions. The recovered CO<sub>2</sub> has a purity of 95% and experiments are underway to inject the captured CO<sub>2</sub> into the concrete mix when it is poured. This then becomes the 'Utilisation' element of Carbon Capture Utilisation and Storage (CCUS). This recovery and utilisation of CO<sub>2</sub> is not likely to be practical for most building construction sites, however, as most concrete is usually transported by truck to the building site. It would be difficult to transport large quantities of CO<sub>2</sub> to building sites for injection into the concrete mix. Injection of CO<sub>2</sub> into fresh concrete would be much easier during the manufacturing process for products like concrete building blocks, however, which take place in a controlled environment. This could then result in a significant quantity of the CO<sub>2</sub> produced during the cement manufacturing process being permanently captured rather than released into the atmosphere.

In summary, there are important and constructive pathways available now to facilitate the capture and permanent storage of CO<sub>2</sub> generated during the manufacturing of cement. These are being tested now by several international cement manufacturing companies, and could result in a significant reduction in the release of CO<sub>2</sub> into the atmosphere. This could also ensure that the use of concrete as an important building component would be sustained without unduly contributing to the release of large quantities of greenhouse gases.

#### 6.5. Huaxin's cement kiln domestic waste cooperative disposal technology

Huaxin Cement is one of the initial cement enterprises in China. With a clinker capacity of 71.42 million tonnes per year, it is the fourth-largest cement producer in China. Huaxin Cement is responding to the national call for green and sustainable development strategy, especially in the research on cement kiln domestic waste cooperative disposal technology<sup>68</sup>.

Huaxin Cement cooperative disposal technology is located in Wuhan. As the largest domestic waste pre-treatment and disposal project in China, it has a total domestic waste treatment capacity of 4 000 tonnes/day, accounting for half of daily domestic waste in Wuhan. This might solve the problem of garbage treatment in the metropolitan area of Wuhan.



Fig. 5.38 Domestic waste disposal flow chart of cement kiln<sup>69</sup>

[http://qikan.cqvip.com/Qikan/Article/Detail?pid=47530967&from=Qikan\\_Search\\_Index](http://qikan.cqvip.com/Qikan/Article/Detail?pid=47530967&from=Qikan_Search_Index)

<sup>68</sup> White Paper on low-carbon Development of Huaxin Cement Co., LTD

<sup>69</sup> Huaxin Cement: being a green industrial upgrade [J]. Environmental Economy, 2013(10):40-43

Huaxin's cement kiln domestic waste cooperative disposal technology has two parts: the ecological pre-treatment of domestic waste and the cooperative post-treatment of the cement kiln production. From garbage to the cement kiln, it entails the following steps: reception, drying, sorting, deodorisation, leachate treatment and calcination. The core concept of this technology is to biochemically, physically and mechanically treat domestic waste, which has a moisture content of 60% and a calorific value of 700 kcal. In doing so, secondary derived fuels and raw materials suitable for cement production can be extracted. In this process, the sewage is treated in the facilities attached to the ecological treatment plant, and malodorous gas is treated by the deodorisation system. Meanwhile, the carbon emission of the plant is as low as 593 kg CO<sub>2</sub>/tonne cement, thus providing a valuable contribution to the CO<sub>2</sub> emission reduction.

In conclusion, the cement kiln domestic waste cooperative disposal technology can help to solve problems of wasted gas, water, residues and dioxins resulting from the process of domestic garbage treatment. It can furthermore provide raw materials and fuel for cement plants. According to an estimate, 60% of the annual domestic waste of China can be disposed of with only 25% of the total production capacity of the cement industry.

## 7. Key messages and recommendations

---

### *Key messages*

1. **The cement industry is one of the largest CO<sub>2</sub> emitting industrial sectors in the world, accounting for about 7% of global carbon emissions.** Being versatile and durable materials, concrete and cement play a prominent role in the construction industry and will continue doing so. Furthermore, they will be important in the development of low-carbon energy as they will be used for the foundations of wind turbines, hydro-electric dams and many other infrastructure projects. The decarbonisation of the cement industry is thus crucial.
2. **The global carbon emission intensity of cement clinker is 815~880 kg/t cement clinker.** In the cement production process, nearly 90% of CO<sub>2</sub> is emitted from two thermochemical processes. One is the use of raw materials such as limestone in the cement calcination process, which accounts for about 50% of CO<sub>2</sub> emissions. The other is burning fuels, which roughly accounts for another 40%. 10% of the remaining CO<sub>2</sub> is emitted from the transport of raw materials and other processes that consume electricity. CO<sub>2</sub> emission intensity varies notably among different countries, mainly because of differences in access to and use of carbon emission reduction technology.
3. **Energy efficiency improvement measures and low-carbon emission technologies are more and more used in the cement production process.** These include low-temperature waste heat power generation technology and the adoption of alternative raw materials and fuel technologies that are still in the demonstration stage, such as calcium carbide slag, oil shale, biomass, green hydrogen, and waste. These measures will foster the development of cement with a low carbon footprint, and will promote a low-carbon development path in conjunction with the progress of CCUS technology.
4. **Producers have been carrying out research and industrial demonstrations of low-carbon technologies for the cement industry.** In Argentina, Canada, China, Croatia, India, South Africa, Sweden and many other countries, cases are studied in various ways on the pathway to CO<sub>2</sub> reduction, especially in the innovative technologies of alternative fuel, low-carbon cement and CCUS.

## Recommendations

The following points summarise our main recommendations for the cement industry towards achieving its carbon neutral target.

### 7.1. Clear, stable and holistic public policies and incentive regulations to encourage carbon emission reduction of the cement industry

Many technologies for carbon reduction in the cement industry are already mature and available. However, they still require incentivising regulations in order to be deployed on a large scale. Holistic policies will be needed to encourage public and private stakeholders to act towards achieving the target.

### 7.2. Deploying low-carbon available technology and improving research and development

The major emission reduction technologies include improving energy efficiency, using alternative raw material, using alternative fuel, developing cement with a lower carbon footprint, and CCUS. It is important that, as soon as possible, the best low-carbon technologies with high maturity be deployed. Research and development on new types of technology, new processes and new cement / concrete compositions are also important as they offer new possibilities for the cement industry to tackle climate change.

### 7.3. The CCUS will certainly be required to reach the low-carbon objectives

For the cement industry, carbon emissions do not only result from the source of energy being used and how that energy is obtained. The production process itself, for example the decomposition of the major feedstock (limestone), causes a large number of emissions. This cannot be solved by the use of low-carbon electricity or hydrogen. While low-carbon materials are used as substitutes to decrease the use of limestone, CCUS may be more important for the cement industry. However, such technology will not be massively deployed until it is economically feasible.

### 7.4. Developing and updating benchmarks and standards

Benchmarks for production processes will encourage cement companies and industrial players to identify performance gaps and achieve emission reduction targets. Generally, standards provide consistency for producers, users and consumers. As new types of cement, such as calcium aluminate cement, Portland Limestone Cement, fly ash cement, and other SCMs and admixtures, are being developed, the development and update of cement standards will provide cement users with instruction and flexibility, and further increase the market for currently available high-performance, lower carbon products. This will greatly help the cement industry reduce emissions.

### 7.5. Promoting close cooperation between cement and other industries and achieve overall carbon emission reduction

Non-recycled plastic, paper, fibers, and fabrics are excellent lower-carbon substitutes for coal. Granulated slag from steel blast furnaces and fly ash from coal-fired power plants can substitute for clinker. Using these materials as fuels and feedstocks, the cement industry can provide valuable environmental and community benefits, diverting or recovering industrial secondary materials from land disposal while reducing the emissions intensity of its products. It can also offer a more efficient way to treat domestic waste than incineration and landfilling. Lastly, finished concrete and concrete aggregates could act as carbon sinks over the useful life and end-of-life phases of concrete projects. Cooperation across sectors should be fostered in order to achieve the overall carbon reduction target.

## List of abbreviations and acronyms

---

<b>AFs</b>	Alternative Fuels
<b>AQC</b>	Air Quenching Cooler
<b>CAP</b>	CO <sub>2</sub> Capture unit
<b>CCR</b>	Calcium Carbide Residue
<b>CCS</b>	Carbon Capture and Storage
<b>CCUS</b>	Carbon Capture, Utilisation and Storage
<b>CDM</b>	Clean Development Mechanism
<b>CEM1</b>	A type of portland cement defined by the European cement standard EN 197-1-2011. This cement is made of 95%~100% cement clinker with 0~5% blended material.
<b>Cembureau</b>	European cement association
<b>CSI</b>	Cement Sustainability Initiative
<b>CST</b>	Concentrated Solar Thermal
<b>EE</b>	Energy Efficiency
<b>EU-ETS</b>	European Union Emissions Trading System
<b>GBFS</b>	Ground Blast Furnace Slag
<b>GCCA</b>	Global Cement and Concrete Association
<b>GHG</b>	Greenhouse Gas
<b>GNR</b>	Getting the Numbers Right
<b>IEA</b>	International Energy Agency, based in Paris
<b>LC3</b>	Limestone Calcined Clay Cement
<b>MBM</b>	Meat and Bone Meal
<b>MSW</b>	Municipal Solid Waste
<b>OPC</b>	Ordinary Portland Cement
<b>PH</b>	Preheater
<b>PLCs</b>	Portland Limestone Cements
<b>PVC</b>	Polyvinyl Chloride
<b>PPC</b>	Portland-Pozzolana Cement
<b>RDF</b>	Refuse Derived Fuel
<b>SCMs</b>	Supplementary Cementitious Materials
<b>SRF</b>	Solid Recovered Fuel
<b>tce</b>	tons of coal equivalent
<b>TSR</b>	Thermal Substitution Rate
<b>WBCSD</b>	World Business Council for Sustainable Development
<b>WHR</b>	Waste Heat Recovery
<b>WHRS</b>	Waste Heat Recovery System

---

## CHAPTER 6. IRON AND STEEL INDUSTRY

### Members of the Working Group

**Àlvarez Pelegry Eloy**, Spain (Co-chair)

**Anyaeji Otis**, Nigeria

**Cai Rui**, China

**Chang Woong-Seong**, Republic of Korea (Co-chair)

**Fredenberg Lennart**, Sweden

**Imasogie Benjamin I.**, Nigeria (deceased 2021)

**Melvin Christopher**, United Kingdom

**Palotás Arpad N.**, Hungary

**Park Chinho**, Republic of Korea

**Sohn Il**, Republic of Korea

**Speer John**, United States

The authors regret the passing away of **Professor Benjamin I. Imasogie**, a deeply engaged member of the Working Group. They acknowledge his valuable contribution by dedicating this chapter to him.

## Table of Contents

---

<b>Executive Summary</b> .....	218
<b>1. Introduction to the industrial sector of iron and steel</b> .....	219
<b>2. Current situation</b> .....	220
2.1. Current production volumes worldwide and in different regions. ....	220
2.1.1. Current situation in Europe, the United States of America and Asia .....	221
2.2. Steel demand and markets. ....	222
2.3. Steel production processes. ....	226
2.4. Steel and energy use .....	228
2.5. CO <sub>2</sub> emissions .....	229
2.5.1. Total global emissions from steel industry .....	229
2.5.2. CO <sub>2</sub> emissions from different technologies / processes and different sources. ....	229
2.5.3. Contribution of the steel industry to net-zero emissions .....	232
2.5.4. Mining .....	233
<b>3. Existing, forthcoming and possible breakthrough solutions</b> .....	235
3.1. Introduction to decarbonisation technologies. ....	235
3.2. Existing technologies .....	236
3.2.1. Making the most of recycled raw materials: the example of scrap .....	236
3.2.2. Improving the efficient collection and sorting of scrap .....	237
3.2.3. Optimising the whole transport system and methods including the use of low-carbon or low carbon fuels for transport. ....	237
3.2.4. Electrification of heating and heat-treatment processes .....	237
3.2.5. Bio-based gas and low-carbon hydrogen as substitute for fossil fuels in heating and heat-treatment processes. ....	238
3.3. Technologies in progress .....	238
3.3.1. Direct reduction of iron ore by hydrogen in shaft furnace .....	238
3.3.2. Direct reduction of iron ore by hydrogen in fluidised bed reactor. ....	240
3.3.3. Bio-coke injection in Blast furnaces (BF / BFO) .....	240
3.3.4. Bio-coke for the reduction of iron ore in powder production .....	240
3.4. Need for further R&D for breakthrough solutions. ....	240
<b>4. Recycling: scrap metal combined with direct reduction or arc furnaces</b> .....	241
4.1. Overview .....	241
4.2. Current status of iron scrap trade, supply and specifications. ....	243
4.2.1. Current status of global ferrous scrap trade and supply .....	243
4.2.2. Status of ferrous scrap recycling and utilisation technologies. ....	245
4.2.2.1. Scrap substitutes for the dilution of tramp elements. ....	246
4.2.2.2. Physical and chemical methods to remove impurities. ....	247
4.2.3. Implications and Future Prospects. ....	247

<b>5.</b>	<b>Challenges related to the decarbonisation of the manufacturing processes</b>	248
5.1.	Investment needs, stranded assets and return of capital	248
5.2.	Access to and cost of low-carbon hydrogen and regulations	248
5.3.	Political and economic regulations and incentives as driving forces to implement low-carbon technologies	250
5.4.	Availability and reliability of low-carbon electricity	250
5.5.	Trade barriers	251
5.6.	Permission processes and political instruments	251
5.7.	Bridging the skills gap	251
<b>6.</b>	<b>Case Studies</b>	252
6.1.	China: Decarbonisation Plan and hydrogen metallurgy	252
6.1.1.	Action Plan for carbon emission decrease in China	252
6.1.2.	China Baowu Steel Group Corporation Ltd.	253
6.1.3.	HBIS Group CO., Ltd.	253
6.2.	Japan: COURSE 50	254
6.3.	Republic of Korea: POSCO	254
6.4.	Sweden: HYBRIT (Hydrogen Breakthrough Ironmaking Technology)	256
6.4.1.	Introduction	256
6.4.2.	Technology	256
6.4.3.	Timeline for low-carbon steel production	257
6.5.	United States of America	257
6.6.	Further Cases	258
6.6.1.	ArcelorMittal, France, Germany, and Spain	258
6.6.2.	TATA Steel NL	258
6.6.3.	H2 Green Steel, Sweden	259
6.6.4.	Thyssenkrupp Steel, Germany	259
<b>7.</b>	<b>Key messages and recommendations</b>	260
7.1.	On increasing scrap use	260
7.2.	On modifications that allow existing facilities to reduce CO <sub>2</sub> emissions	260
7.3.	On a potential acceleration of the timing of CO <sub>2</sub> emissions reduction	260
7.4.	On Research and Development	261
7.5.	On Education and Training	261
7.6.	On Permitting	261
7.7.	On global cooperation and partnerships	261
<b>8.</b>	<b>List of abbreviations and acronyms</b>	262

## Executive Summary

---

This chapter analyses the iron and steel industries and suggests avenues for the reduction of GHG emissions over the next 30 years.

First of all, the current situation has been reviewed, in terms of worldwide production volumes, demand and market trends, production processes, energy use and CO<sub>2</sub> emission status. In 2021, the production of crude steel increased to around 1 950 million tonnes, and demand for steel is expected to inevitably increase as populations grow and nations around the world seek to improve their standards of living.

The production of steel remains a CO<sub>2</sub>- and energy-intensive activity. In 2019, to produce some 1 880 Mt steel, the iron and steel sector accounted for around 10 000 TWh of global energy consumption, which represented 20% of the industrial energy use and 8% of the total final energy use. On average, every metric ton of steel produced led to the total emission of 1.85 tons of CO<sub>2</sub>, including direct process emissions (1.4 tCO<sub>2</sub>) and indirect emissions such as associated with electricity from the grid; the direct emissions from the steel industry were of the order of 2.6 GtCO<sub>2</sub>, representing between 7 and 9% of global anthropogenic CO<sub>2</sub> emissions.

Steelmakers use and consider various existing and forthcoming solutions, such as making the maximum use of scrap, bio-coke injection, CCUS strategies, the direct reduction of iron ore with hydrogen, etc. in order to find pathways to decarbonisation. Globally, the route to decreasing emissions is likely to be a transitional one; regional interests, geographical and local conditions, and technological availability being the limiting factors that impede the rate of progress.

The use of ferrous scrap is expected to gradually increase along with the growing emphasis on greenhouse gas regulations. Integrated steel mills typically use about 15% of ferrous scrap on average together with molten hot metal. Increasing the use of ferrous scrap can reduce the amount of greenhouse gas generated per tonne of molten steel. In line with the strengthening of environmental regulations, further developments are expected to be required in power-saving technologies involving for example VOC control technology, electric furnace heating technology, and preheating methods, along with processing technology to remove impurities from iron-based scrap.

The main challenges related to the decarbonisation of the steel manufacturing processes have been reviewed. These include: the scale and efficiency of investment, availability of low-carbon hydrogen and electricity, investment needs, stranded assets and return of capital, approval from authorities and political decision makers, skill shortage, etc.

Worldwide case studies have also been introduced in the report. These include China Baowu's hydrogen-based shaft furnace direct reduction technology, and the hydrogen metallurgy demonstration project of the HBIS group, which has an expected annual output of 1.2 million tonnes hydrogen steel and is to be the most advanced hydrogen production and reduction technology in the world. In the Republic of Korea, POSCO plans to build its Hydrogen Reduction (HyREX) pilot plant for low-carbon ironmaking based on fluidised bed reduction technology by 2028, and Swedish SSAB, LKAB and Vattenfall use the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) to eliminate the formation of CO<sub>2</sub> by using low-carbon hydrogen as reductant and energy source. In the case of HYBRIT, sponge iron is produced with hydrogen gas as the reductant. Using this technology, SSAB has decided to phase out all of its five blast furnaces before 2030 in Sweden and Finland. In addition, significant advances are being made by world-leading steel makers in Japan, USA and Europe.

## 1. Introduction to the industrial sector of iron and steel

---

The members of the Working Group come from diverse backgrounds such as steelmaking, energy, material sciences, metallurgy, chemistry, the engineering of steelmaking equipment, catalysis, electrochemistry, etc. The Group has interviewed experts on steel technology, and in particular hydrogen-based steelmaking from HYBRIT (Sweden), POSCO (Republic of Korea), and Northeastern University, Shenyang (China).

The modern steel industry has already a long tradition, starting in the 1850s when the Bessemer Converter was invented by Sir Henry Bessemer. However, in China, under the Song Dynasty, a similar process was already known about eight hundred years earlier, albeit not on an industrial scale. Iron was indeed known as a major material since the Iron Age, which followed the Bronze Age from about 1200 BC.

After the Industrial Revolution, the BF-BOF process provided a versatile and universal material essential to our civilisation. However, the recent climate changes caused by the accumulation of CO<sub>2</sub>, known as the Keeling Curve since 1956, require an industrial transformation for the decarbonisation of the largely carbon-based steel industry.

This chapter introduces current process technologies already resulting in lower greenhouse gas emissions than previous ones, already existing but still not widely deployed (although they do lead to further reductions in Greenhouse Gas emissions), as well as radically new technologies, deployed on the scale of pilot projects, e.g., hydrogen-based melting and reduction processes. Case studies illustrate these revolutionary processes, which do, however, depend on the availability of 'green' hydrogen, produced via water electrolysis using low-carbon electricity, which does not come for free and is mostly available in an intermittent mode.

Furthermore, the chapter analyses the recycling of steel (scrap), which raises its own issues as different steel products for different uses incorporate a variety of other elements, such as manganese, copper, nickel, etc. to acquire the required characteristics (strength, elasticity, corrosion resistance, ductility, etc.), which cannot be easily separated from scrap. It also compares the availability of scrap in developing countries with that in already developed and industrialised countries, which can be a hurdle. Electricity also plays a major role in recycling scrap, using electric arc furnaces (EAF). Last but not least, it also touches on societal acceptability, in particular in relation to Carbon Capture and Storage (CCS).

The decarbonisation of the mining of iron ore is also briefly covered.

It should be mentioned that performance improvement of steel materials may indirectly result in further reductions in CO<sub>2</sub> emissions.

The chapter does not cover the end-products other than at the end of their lifecycle (scrap).

## 2. Current situation

### 2.1. Current production volumes worldwide and in different regions

In 2021, the production of crude steel increased to around 1 950 million tonnes (Mt)<sup>1</sup>. Despite a sharp decrease in demand in 2020 due to the COVID-19 pandemic<sup>2</sup>, production in China increased between 2019 and 2020 by 5.2%, while production in India and other parts of Asia decreased. Steel production in Europe (EU 28) decreased by more than 12% and US production decreased by as much as 17% in 2020 compared to 2019.

The map below shows the 20 largest steel producers in the world. In addition to China, India, the United States of America, Russia, Japan and the Republic of Korea are the largest steel producing countries<sup>3</sup>. Steel production in the world is dominated by China, with almost 60% of world production. The other 40% of total production are evenly distributed among other regions.



Fig. 6.1. Top 20 steel-producing countries/regions 2021 (million tons)  
<https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2022-infographic.pdf>

Steel production worldwide has been increasing continuously particularly since the year 2000, as can be seen in the graph below.

<sup>1</sup> [World Steel in Figures 2022 - worldsteel.org](https://worldsteel.org)

<sup>2</sup> World crude steel production reached 1,878 million tonnes (Mt) for the year 2020, down by 0.9% compared to 2019, according to data from World Steel Association (WSA).

<sup>3</sup> World steel information in figures and graphs – see: [WST01-i-84 WSIF infographic 2022 \(worldsteel.org\)](https://worldsteel.org)

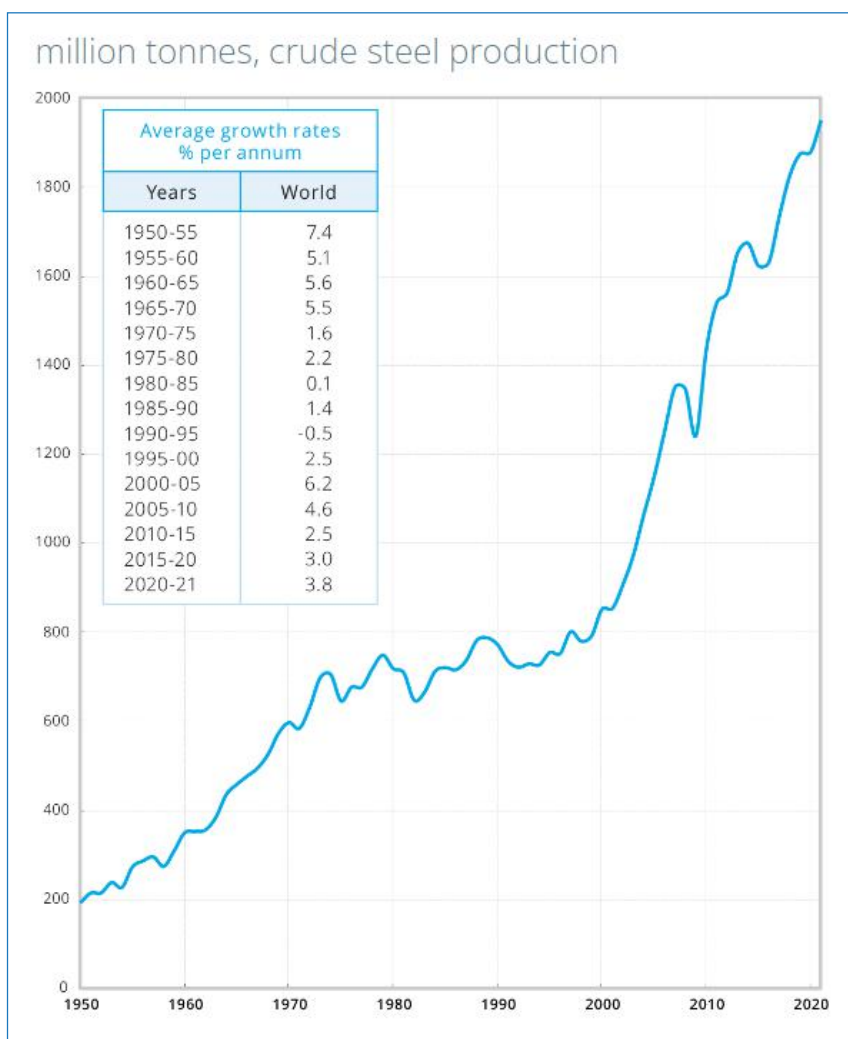


Fig. 6.2. Evolution of global steel production since 1950

World Steel Association

<https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2022.pdf>

### 2.1.1. Current situation in Europe, the United States of America and Asia

In the year 2020, steel production in Europe amounted to 139 million tonnes (Mt). The top producers, which produce more than 10 Mt/yr, are Germany, France, Italy and Spain. According to the European Steel Association - EUROFER, European crude steel production for all qualities was around 152 million tonnes for 2021, while it had decreased over the last 10 years, including for the UK. During the pandemic year 2020, there was another sharp decrease of just over 10%.

In the United States, around 71 million metric tonnes of steel were produced in 2020. Electric arc furnace production exceeded 70% of total steel production. Production exceeded 80 million tonnes in 2018 and 2019, before the COVID-19 pandemic. Over the past decade, the share of EAF production has increased from about 60%<sup>4</sup>. There has been a gradual increase in EAF production capacity, and a decrease in that of BOF.

China, India, and Japan are the major steel producers with 1 064.8 million tonnes, 100.4 and 83.2 million tonnes respectively. China accounts for 56.7% of total world production and India and Japan for 5.3% and 4.4% respectively. Production in other Asian countries amounts to 7.5%. Asian countries thus represent nearly three quarters (73.9%) of the world crude steel production. In some countries, such as the Republic of Korea, the production of steel is expected to decrease after reaching a peak in the next few years. Nevertheless, the carbon neutrality issue remains important.

<sup>4</sup> Statista 2022

2.2. Steel demand and markets

A view of the supply and final demand considering the type of products of finished steel is shown in the following figure, in which the steel in final products is classified into consumer goods, mechanical and electrical equipment, vehicles, infrastructure, and buildings.

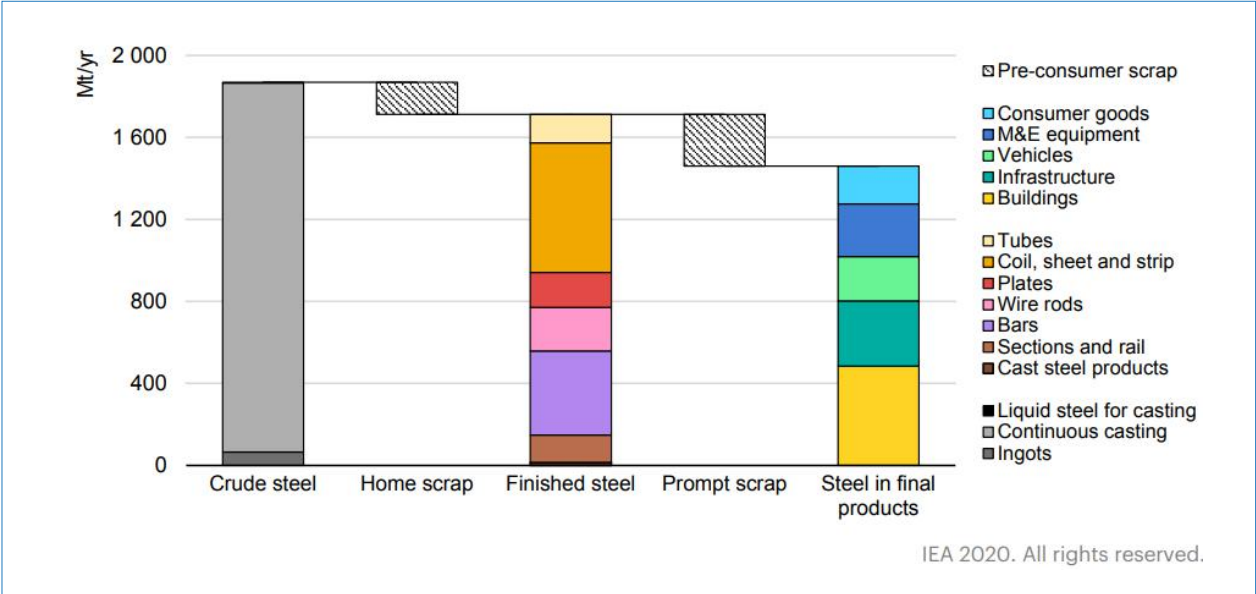


Fig. 6.3. Global steel production by product and demand segment in 2019  
(For the definitions of home scrap and prompt scrap, see § 4.1)

Source: “Iron and Steel Technology Roadmap. Towards a more sustainable steelmaking”. IEA (2020)<sup>5</sup>

In terms of world trade, the following table allows exports and imports to be seen by country and region. It shows that extra-regional imports and exports represent a considerable trade volume, with a level of nearly 400 Mt of exports / imports that may be compared with the previously mentioned 1 877 Mt figure of total worldwide production.

<sup>5</sup> Iron and Steel Technology Roadmap: Towards more sustainable steelmaking”. IEA (2020): [https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron\\_and\\_Steel\\_Technology\\_Roadmap.pdf](https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf)

million tonnes

Exporting region \ Destination	European Union (28)	Other Europe	CIS	USMCA	Other America	Africa and Middle East	China	Japan	Other Asia	Oceania	Total imports	of which: extra-regional imports
European Union (28)	95.8	8.4	12.9	0.2	0.6	1.1	2.1	0.3	6.9	0.1	128.4	32.6
Other Europe	7.8	0.8	6.1	0.0	0.7	0.1	0.9	0.6	1.1	0.0	18.2	17.4
CIS	1.0	0.5	10.3	0.0	0.0	0.0	1.6	0.0	0.4	0.0	13.8	3.5
USMCA	4.7	0.8	2.6	14.4	4.5	0.6	1.3	2.1	5.0	0.3	36.4	22.0
Other America	0.9	1.4	1.0	2.8	3.0	0.0	3.1	1.1	1.1	0.0	14.5	11.5
Africa	3.5	3.6	4.1	0.1	0.5	1.8	8.3	1.1	2.6	0.0	25.5	23.6
Middle East	1.3	4.4	3.3	0.1	0.2	5.9	5.1	1.0	4.3	0.0	25.7	19.8
China	1.4	0.2	2.6	0.4	1.5	3.0	-	5.0	23.8	0.0	37.9	37.9
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.9	-	4.2	0.0	5.1	5.1
Other Asia	1.9	1.5	7.9	0.4	0.4	2.4	27.5	18.3	27.3	0.3	88.0	60.7
Oceania	0.2	0.1	0.0	0.1	0.0	0.0	0.7	0.2	1.2	0.2	2.7	2.5
Total exports	118.5	22.0	50.9	18.5	11.4	14.9	51.4	29.8	77.8	1.1	396.3	236.6
of which: extra-regional exports*	22.6	21.1	40.6	4.0	8.4	7.2	51.4	29.8	50.5	0.9	236.6	
Net exports (exports-imports)	-10.0	3.7	37.1	-18.0	-3.1	-36.3	13.5	24.8	-10.1	-1.7		

\* Excluding intra-regional trade marked

Fig. 6.4. World trade in steel by area in 2020<sup>6</sup>

To analyse the challenges for decarbonising steel production, it may be interesting to look at the steel market and the market development of future demand for decarbonised steel material in different market sectors. With the population growth and the development of emerging countries, it is foreseen that overall demand will still increase even if it is decreasing in industrialised countries. Furthermore, the potential decarbonisation of iron and steel production, allied to specific qualities, could give special steels opportunities to develop markets.

<sup>6</sup> <https://worldsteel.org/wp-content/uploads/2021-World-Steel-in-Figures.pdf>

A breakdown of the different types of demand may be seen in the following figure<sup>7</sup>:

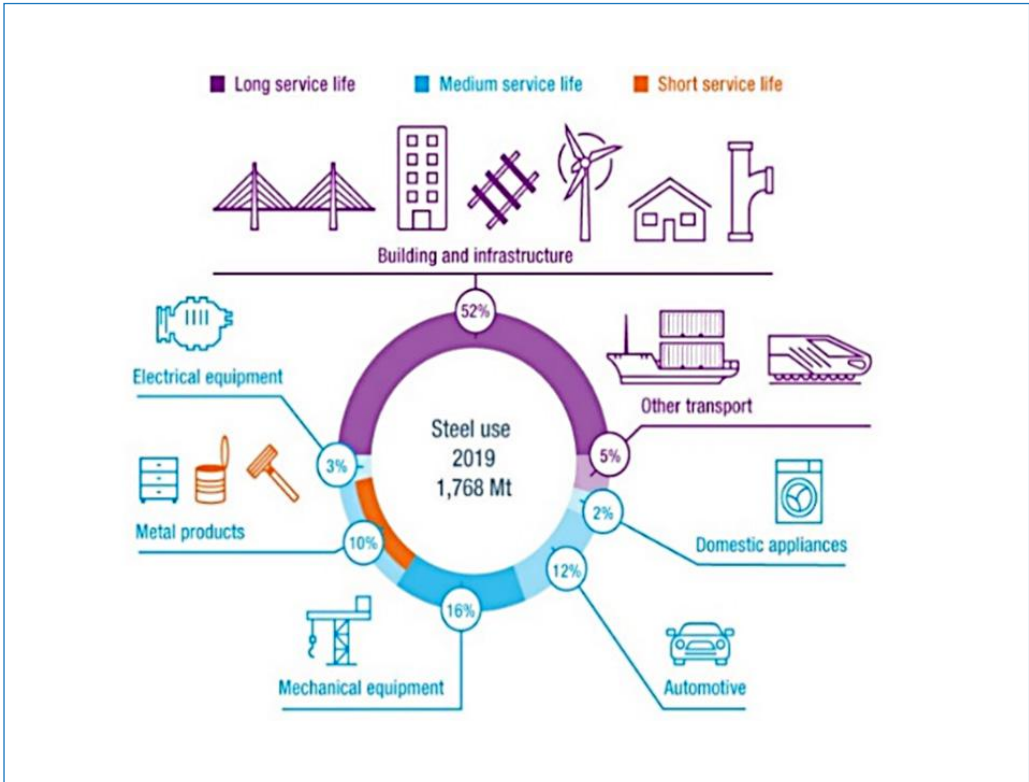
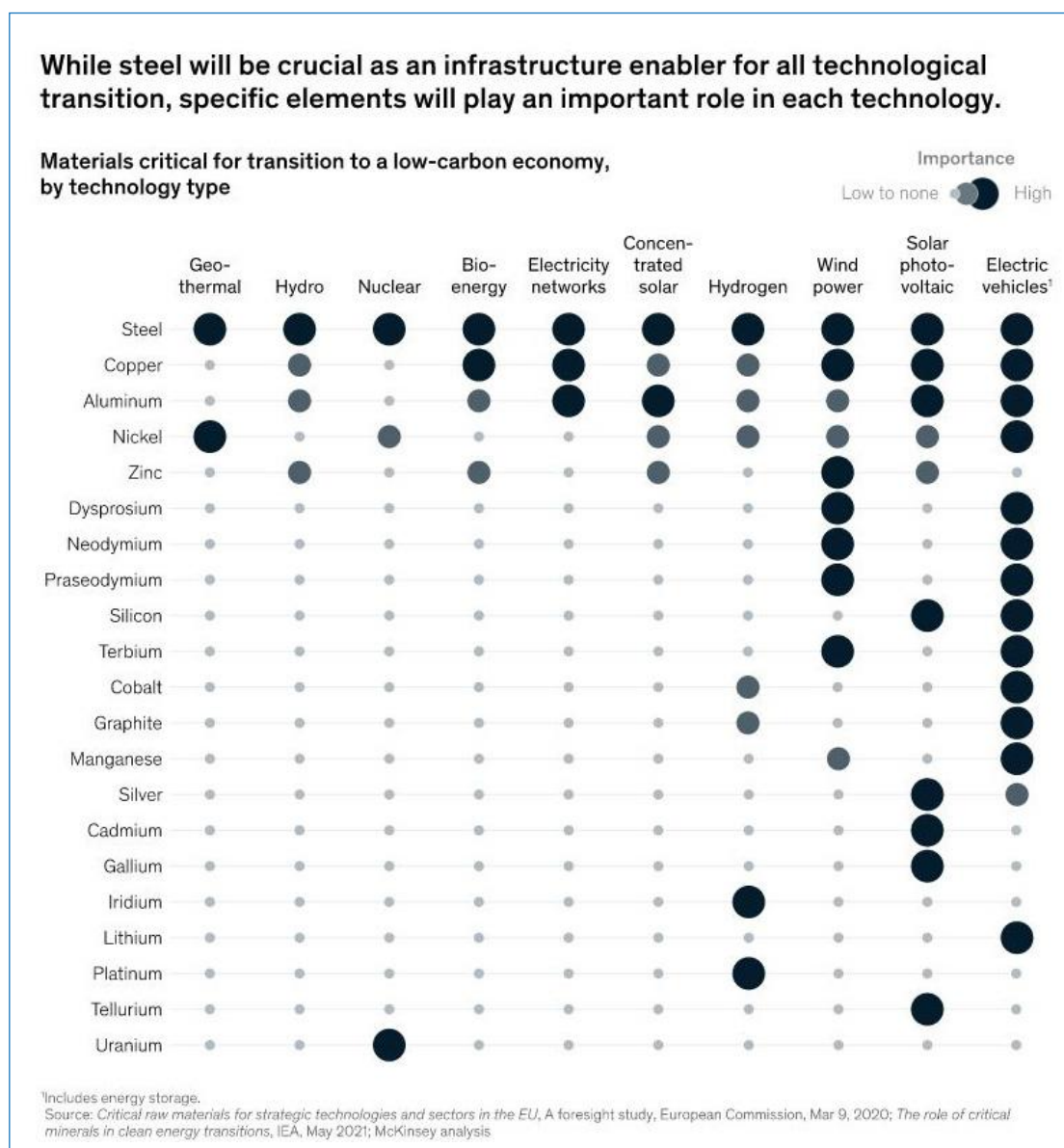


Fig. 6.5. Where steel is used

Steel is considered as a critical material for the infrastructural transition towards a low-carbon economy across every single decarbonisation technology shown in the following figure<sup>8</sup>.

<sup>7</sup> <https://worldsteel.org/steel-topics/steel-markets/>

<sup>8</sup> See next page



**Fig. 6.6.** Critical material for the infrastructural transition towards a low carbon economy across decarbonisation technologies  
Exhibit from “The raw-materials challenge: How the metals and mining sector will be at the core of enabling the energy transition”, January 2022, McKinsey & Company, [www.mckinsey.com](http://www.mckinsey.com). Copyright (c) 2022 McKinsey & Company. All rights reserved. Reprinted by permission.  
<https://www.mckinsey.com/industries/metals-and-mining/our-insights/the-raw-materials-challenge-how-the-metals-and-mining-sector-will-be-at-the-core-of-enabling-the-energy-transition?cid=other-eml-alt-mip-mck&hdpid=7236476e-7fa1-41ea-84f8-6f923bcde51b&hctky=11774778&hlkid=ac-3790c29bd84c798f37850b8edb72fb>

Demand is, however, expected to mainly decrease in developed countries, but it is predicted to swiftly increase in developing countries where rapidly growing economies will more than compensate for this decrease. In addition, steel products for energy sustainability and electrification will likely increase, which will have an impact on product divisions.

In the same report, McKinsey also highlights that a range of feedback loops will drive changes to supply chains alongside technology shifts and material substitution. For steel, such loops could be the re-domiciling of local steel manufacturing across areas of Europe and America to meet national demand, and the creation of a range of new steel grades to meet ever-demanding requirements for electrification and hydrogen transport. This will also affect consumption behaviours and the technologies used where manufacturing is driven by mining economics – issuing less metallurgical coal extraction licenses will indeed drive manufacturing towards alternative fuel and energy sources / processing technologies.

### 2.3. Steel production processes

The following figure presents an ample visual representation of these processes, from raw material production to steel making, including production from scrap<sup>9</sup>.

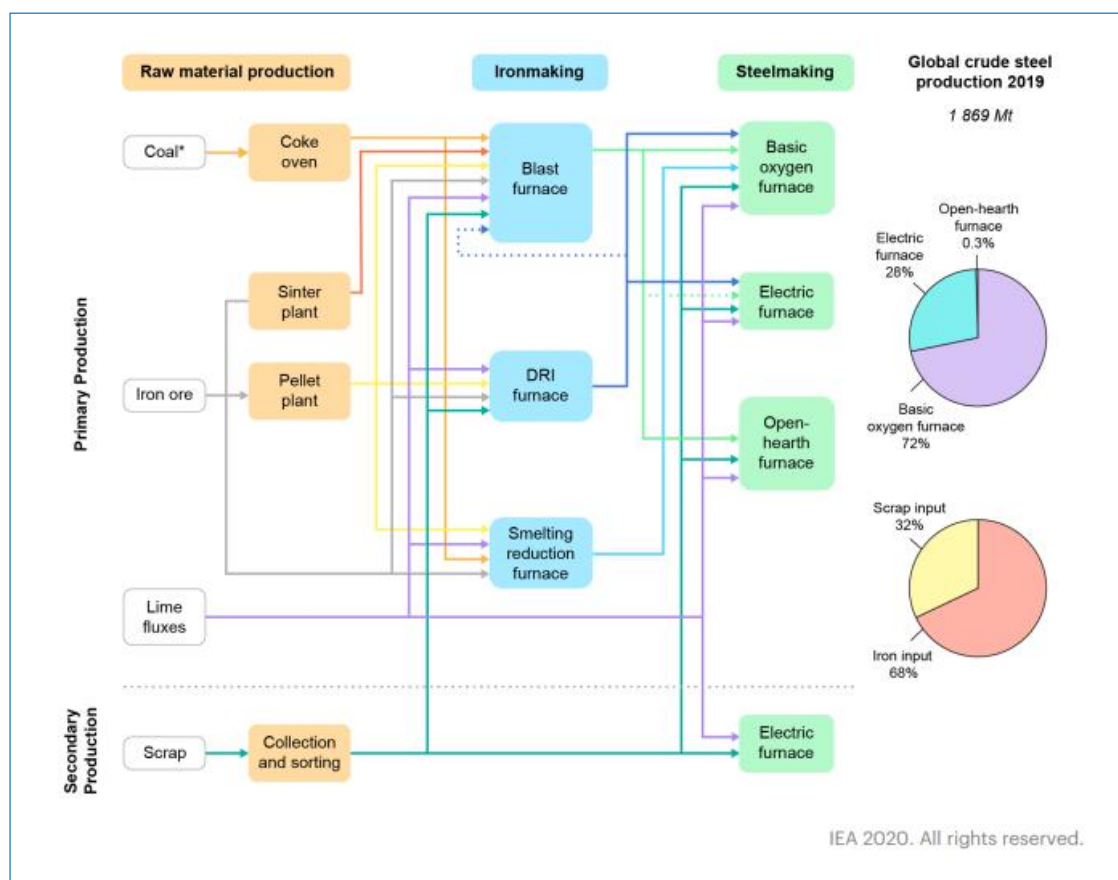


Fig. 6.7. Production processes: from raw material production to steelmaking

More than 80% of crude steel is produced via primary routes using mostly iron ore along with some scrap. The remainder is produced via recycled scrap<sup>10</sup>.

“The main BF-BOF and EAF (both DRI-EAF and scrap- based EAF) routes combined account for 95% of global steel production. Three other process units are also in use today but see very limited penetration.

Smelting reduction is an alternative class of processes for ironmaking that facilitates the use of iron ore fines directly (rather than agglomerated pellets and sinter) and avoids the use of a coke oven or coking coal. Several designs are currently commercially available or under development, but the process is yet to see widespread adoption within the industry. The open-hearth furnace is an outdated alternative to the BOF, and has largely been phased out given the inferior energy performance”<sup>11</sup>.

The DRI-EAF route is worthwhile mentioning. Its main difference with the BF-BOF route is the type of iron that is typically used (high-quality DRI pellets), the state of the material when it is reduced (a solid state in the DRI furnace) and the main reducing agents (hydrogen and carbon monoxide in the DRI-EAF pathway).

In the section dealing with CO<sub>2</sub> emissions, we shall refer to the three routes of:

- BF-BOF
- EAF
- DRI including EAF

<sup>9</sup> Source: [Iron and Steel Technology Roadmap - Towards more sustainable steelmaking \(windows.net\)](#), Page 27

<sup>10</sup> Recycling will be addressed specifically in a later section of this chapter.

<sup>11</sup> IEA, 2020, Iron and Steel Technology Roadmap, Towards more sustainable steelmaking [https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron\\_and\\_Steel\\_Technology\\_Roadmap.pdf](https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf)

The three main production routes are the Blast Furnace (BF)- Basic Oxygen Furnace (BOF), Electric Arc Furnace (EAF), and Open Hearth (OHF). The EAF accounts for 26.3% on a global basis while BOF accounts for 73.2 % and OHF for 0.3 % (worldsteel.org, 2021). The use of an EAF already requires approximately 30 to 40 % less energy compared to the BF/BOF primary route<sup>12</sup>.

In terms of costs, a comparison between different routes including the scrap-based EAF, following IEA (2020), is provided below.

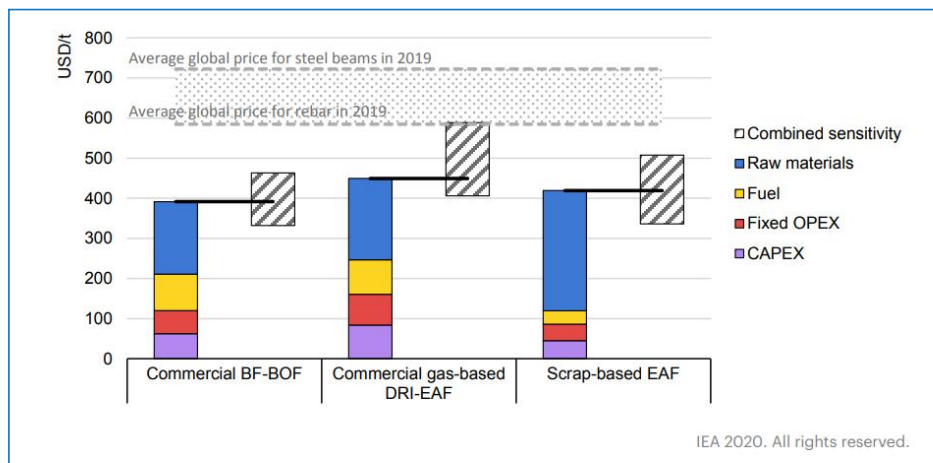


Fig. 6.8. Simplified levelized cost of steel production via major commercial routes

IEA, 2020, Iron and Steel Technology Roadmap, Towards more sustainable steelmaking, Page 31

[https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron\\_and\\_Steel\\_Technology\\_Roadmap.pdf](https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf)

The cost of producing steel is highly sensitive to raw material and energy costs, which typically account for 60-80% of the cost of production.

Crude steel production by process<sup>13</sup> is depicted in the following graph for different countries / regions. As may be seen, there are very significant differences in the use of BOF vs. EAF, China being a clear example of a country using in majority the BOF, while the United States mostly uses the EAF. These differences are relevant to the routes of decarbonisation.

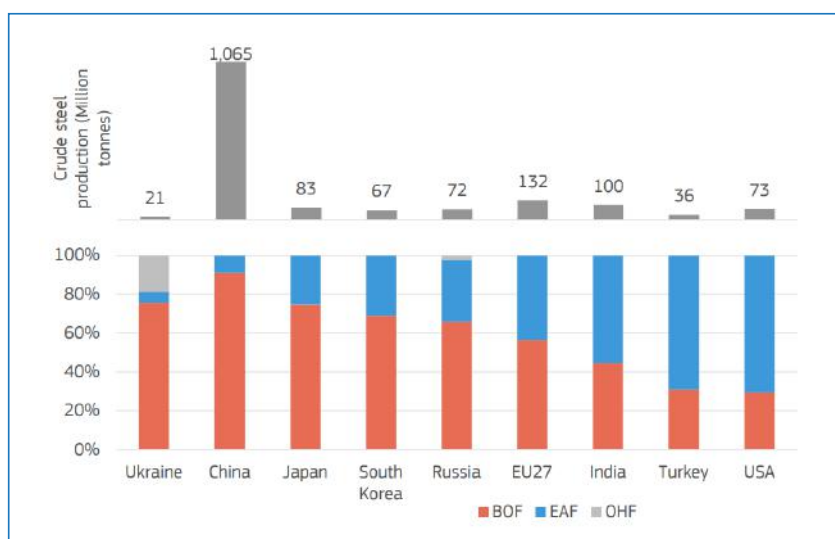


Fig. 6.9. Crude steel production by process and country, 2020

<sup>12</sup> De Beer, E. Worrell and K. Blok, "Future Technologies for Energy-Efficient Iron and Steel Making," Annual Review of Energy and the Environment, Vol. 23, No. 1, 1998, pp. 123-205. doi:10.1146/annurev.energy.23.1.12

<sup>13</sup> Source: JRC Publications Repository - Technologies to decarbonise the EU steel industry (europa.eu), page 11.

Regarding the type of production, China is using oxygen in 90.8% of its processes and electricity in 9.2%. Such rates are 44.5% / 55.5% in India, 74.6% / 25.4% in Japan and roughly 70% / 30% in the Republic of Korea. In the case of China, total production has been increasing regularly during the last decade but the shares of the BOF and EAF have remained constant at about 90% / 10%.

In the case of India, with a production of around 100 Mt (equivalent to about one tenth of China's), production has also been increasing in the past decade by around 50%. However, the proportions between BOF and EAF uses were 40% / 60% respectively in 2011. BOF use increased in the decade up to 44% in 2020; the relative shares of each finally reached 44,5% / 55,5% in the year 2020<sup>14</sup>.

Europe, as has been said, has been experiencing continuous decline in production, (except in 2017, 2018 and 2014). Yet the BOF / EAF shares have been rather stable, on the level of 57% / 43%.

## 2.4. Steel and energy use

The production of steel remains a CO<sub>2</sub>- and energy-intensive activity. In 2019, the iron and steel sector accounted for around 10 000 TWh of global energy consumption, which represented 20% of the industrial energy use and 8% of the total final energy use to produce some 1 880 Mt steel<sup>15</sup>.

Coking coal alone accounted for about 16% (872 million tonnes of coal equivalent – 7 099 TWh) of global coal demand (5 530 Mtce – 45 020 TWh) in 2019. “Electricity and natural gas account for most of the remaining energy demand in the iron and steel sector, in almost equal measure. The steel industry accounted for 2.5% (90 billion cubic meters [bcm]) of global gas demand and 5.5% (1 230 terawatt hours [TWh]) of global electricity demand in 2019”<sup>16</sup>. On the other hand, the off gases of the different processes contain energy (6GJ – 1.666 MWh per tonne of crude steel produced) for use in other processes.

The following figure shows the evolution of final energy consumption in the steel industry.

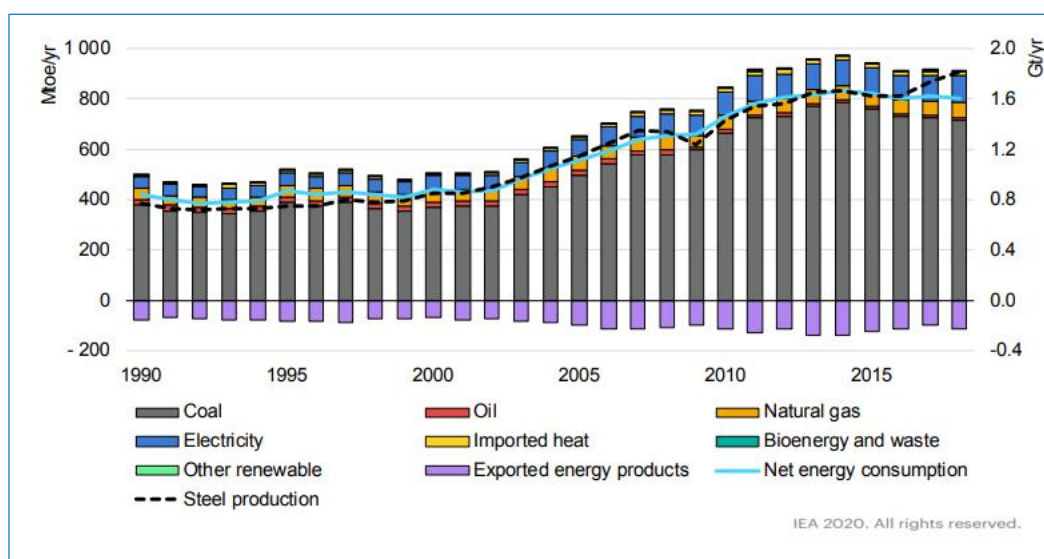


Fig. 6.10. Final Energy consumption in the steel industry

IEA, 2020, Iron and Steel Technology Roadmap, Towards more sustainable steelmaking, Page 36,

[https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron\\_and\\_Steel\\_Technology\\_Roadmap.pdf](https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf)

The energy intensities of the main production routes are the following, according to the IEA and the World Steel Association.

<sup>14</sup> <https://worldsteel.org/zh-hans/steel-by-topic/statistics/world-steel-in-figures/>

<sup>15</sup> [iea.org](https://www.iea.org/) and [worldsteel.org](https://www.worldsteel.org/)

<sup>16</sup> IEA (2020). *Iron and Steel Technology Roadmap. Towards more sustainable steelmaking*

Methodology	BF-BOF	Scrap-based EAF	Natural gas-based DRI-EAF
IEA	21.4 GJ/t (5.94 MWh/t)	2.1 GJ/t (0.58 MWh/t)	17.1 GJ/t (4.75 MWh/t)
worldsteel	22.7 GJ/t (6.31 MWh/t)	5.2 GJ/t (1.44 MWh/t)	21.8 GJ/t (6.06 MWh/t)

Note: worldsteel reference values are adjusted to match the IEA "crude steel boundary" described above. Differences between the IEA and worldsteel values shown here are mainly attributable to the treatment of electricity.

Fig. 6.11. Energy intensities of main production routes

IEA (2020) Iron and Steel Technology Roadmap, Towards more sustainable steelmaking, Page 42

## 2.5. CO<sub>2</sub> emissions

### 2.5.1. Total global emissions from steel industry

On average, every metric ton of steel produced led to the total emission of 1.85 tons of CO<sub>2</sub>, including direct process emissions (1.4 tCO<sub>2</sub>) and indirect emissions such as associated with external electricity; the direct emissions from the steel industry were of the order of 2.6 GtCO<sub>2</sub>, representing between 7 and 9% of global anthropogenic CO<sub>2</sub> emissions<sup>17</sup>.

The level of CO<sub>2</sub> emissions has been increasing consistently with the previous growth in steel production. Indeed, in the decade 1990-2000, total production were at the level of 800 Mt, rising to 1 400 Mt in 2010 and 1 850 Mt in 2020. Growth rates have been variable, yet, since 2000, they have been in the range of 2,5% to 6,2% for the five-year periods<sup>18</sup>.

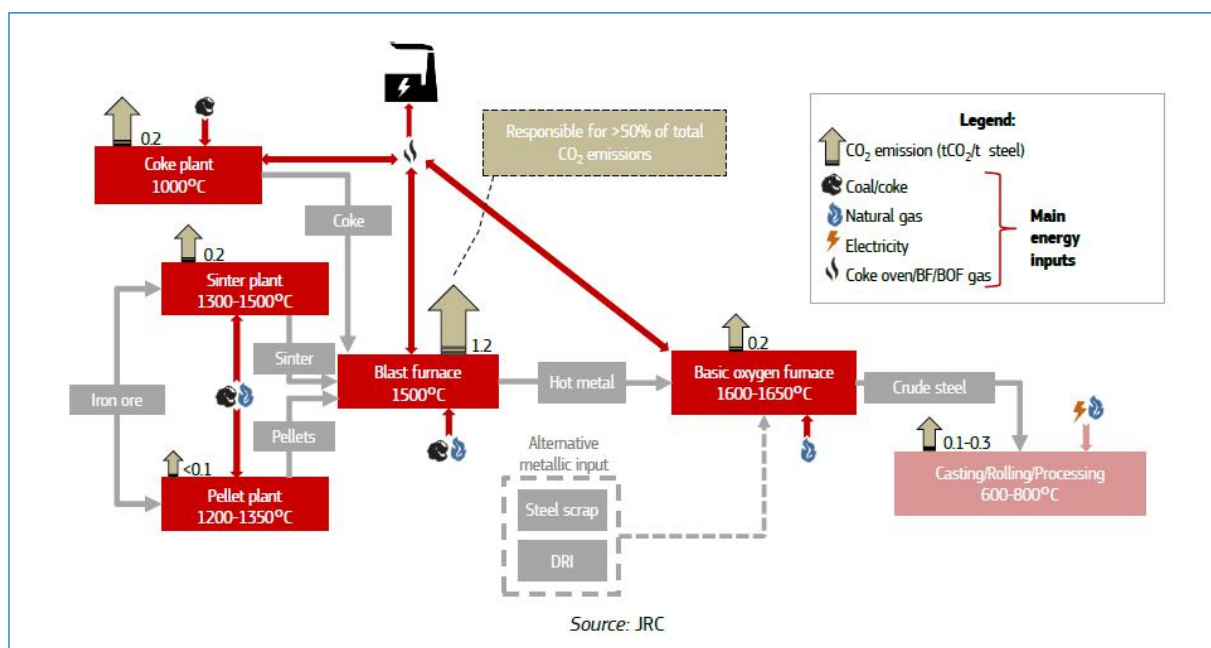
### 2.5.2. CO<sub>2</sub> emissions from different technologies / processes and different sources

This section is based on the comparisons drawn by the Joint Research Centre from the European Commission (2022)<sup>19</sup>. "While both the primary and secondary steelmaking routes are very energy-intensive industrial processes, they can have vastly different CO<sub>2</sub> emission intensities. In the BF-BOF steelmaking route, carbon is not only an energy input but also necessary to bind and remove oxygen from iron ore, resulting in process CO<sub>2</sub> emissions. This processing step in the blast furnace is the most CO<sub>2</sub>-intensive, responsible for over 50% of the total CO<sub>2</sub> emissions of the final product. All other processing steps in the integrated steelmaking route, from preparing the raw materials in the coke and sinter plants, to producing and rolling the steel products emit CO<sub>2</sub> from the combustion of fossil fuels required to reach the high processing temperatures [*this is shown in Figure 6.12. below*]. Attributing emissions to each specific process is not straightforward, since waste gases are recirculated within the steel plant to various sub-processes, including internal power plants, as well as to external power plants. Furthermore, steel plants can buy input products, such as pellets or coke, which lowers the CO<sub>2</sub> emissions occurring at the specific steelmaking site. On average, the total BF-BOF route emits around 1.9 tCO<sub>2</sub>/t crude steel, however there is a wide variability between countries and plants depending on the efficiency of energy and materials use".

<sup>17</sup> [iea.org](https://www.iea.org) and [worldsteel.org](https://www.worldsteel.org)

<sup>18</sup> [PowerPoint Presentation \(worldsteel.org\)](#)

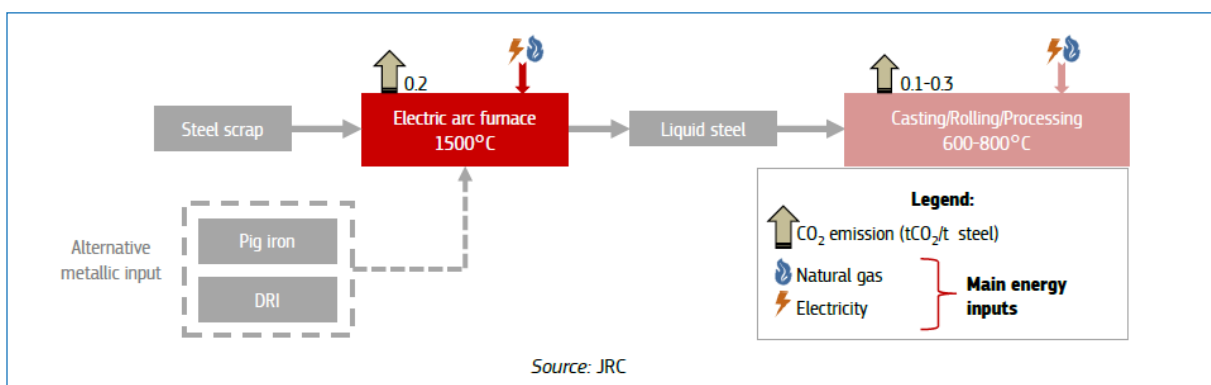
<sup>19</sup> Sommers, J. (2022). "Technologies to decarbonise the EU steel industry". Joint Research Centre.



**Fig. 6.12.** Simplified flow diagram and CO<sub>2</sub> emissions of the BF-BOF route, not including the EAF

Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-47147-9 (online), doi:10.2760/069150 (online), JRC127468, Page 16  
<https://publications.jrc.ec.europa.eu/repository/handle/JRC127468>

“The secondary steelmaking route is largely electrified. Small amounts of natural gas and coal are used in the electric arc furnace to provide additional heat and for slag foaming, and an even smaller proportion of CO<sub>2</sub> emissions are due to the consumption of the graphite electrodes in the EAF, which together contribute some 0.06 to 0.1 tCO<sub>2</sub>/t steel of direct emissions (Echterhof, 2021). [Figure 6.13. below illustrates the CO<sub>2</sub> emissions in the EAF process]. A typical EAF consumes around 500 kWh of electricity per tonne of steel. At the current average CO<sub>2</sub> intensity of electricity in the EU, the total (direct and indirect) emissions from EAF steel melting are around 0.2-0.3 tCO<sub>2</sub>/t steel. The indirect emissions from electricity consumption, around 0.1-0.2 tCO<sub>2</sub>/t steel, would be avoided if the EAF used low-carbon electricity”.

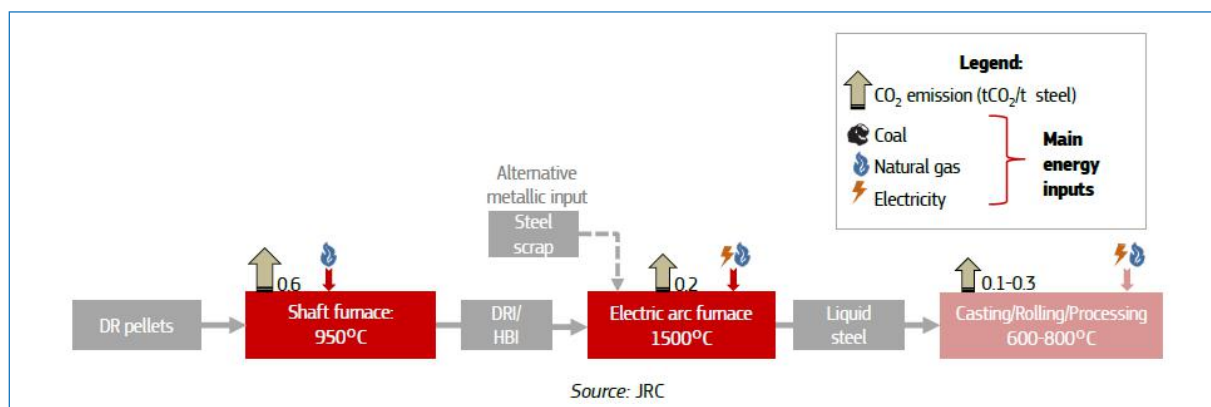


**Fig. 6.13.** Simplified flow diagram and CO<sub>2</sub> emissions of the EAF route

Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-47147-9 (online), doi:10.2760/069150 (online), JRC127468, Page 16  
<https://publications.jrc.ec.europa.eu/repository/handle/JRC127468>

“A number of different processes have emerged over the past fifty years which achieve the direct reduction of iron ore without the need for blast furnaces or coke (thus dispensing also with the need for coke ovens), referred to as Direct Iron Reduction (DRI). In these processes, iron ore is reduced to metallic iron in its solid state, below the melting temperature of iron, by reduction gases composed of a mixture of CO and H<sub>2</sub>. The direct-reduced iron is then generally used as a feedstock for EAFs. The main type of technology that has been

commercialized is shaft furnace-type reactors, such as those developed by Midrex and HYL/Energiron<sup>20</sup>. In both cases, the shaft furnace uses reformed natural gas to reduce iron ore pellets. This process (Fig. 6.14.) emits between 30% and 60% less CO<sub>2</sub> than through the BF-BOF route (Cavaliere, 2019; Sarkar et al., 2018). Due to the need for abundant, cheap natural gas, most shaft furnace DRI plants are situated in natural gas-rich countries. In 2019, global DRI production was 108 Mt, compared to 1 281 Mt of pig iron”.



**Fig. 6.14.** Simplified flow diagram and CO<sub>2</sub> emissions of the direct reduction route, including EAF  
Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-47147-9 (online), doi:10.2760/069150 (online), JRC127468, Page 17  
<https://publications.jrc.ec.europa.eu/repository/handle/JRC127468>

“In India, the number one DRI producer worldwide, a large amount of DRI plants are rotary kilns that use coal instead of natural gas. This coal-based process is around three times as CO<sub>2</sub>-intensive as natural gas, making coal-based DRI the most CO<sub>2</sub>-intensive steelmaking route (Carpenter, 2012).

Shaft furnace DRI processes use iron ore pellets as feedstock, which are typically higher grade (higher iron content, lower gangue levels) than blast furnace pellets. The supply of DRI grade pellets is limited (Midrex, 2018), and other technologies that can allow the use of lower-quality iron ore are also being considered by industry.

Worth noting also are other upcoming ironmaking technologies, commercially available but deployed at a small scale, which can reduce directly iron ore fines. These processes thereby do not need to agglomerate (by pelletizing or sintering) the iron ore. These technologies include two-stage smelting reduction processes (e.g., Finex), where the iron ore is pre-reduced in a fluidized bed, then charged with coal into a melter-gasifier to make hot metal, or two-stage fluidized bed processes which reduce iron ore fines to DRI (e.g. Circored)”.

Another upcoming DRI process is the HYBRIT (Hydrogen Breakthrough Ironmaking Technology) initiative in Sweden. The HYBRIT project is set up to develop a low-carbon value chain for iron and steel production using low-carbon electricity and hydrogen. The technology involves replacing the blast furnace process with a direct reduction process. The goal is to have a unique value chain, from mining to low-carbon steelmaking. Details are described in *Section 6., Case Studies*.

Other cases include those of the Baowu Steel Group in China and of POSCO in the Republic of Korea. They will be described in *Section 6., Case Studies*.

An interesting comparison of the three main routes, besides other alternatives, is shown in *Table 6.1..* As may be seen, it differentiates primary from the secondary steel production.

<sup>20</sup> Midrex Technologies Inc. is an American company based in North Carolina and HYL Energiron is based in Italy. Both are world leaders in direct reduction technologies (DRI).

<b>Table 1.</b> Specifications of current commercially available and new transformative low CO <sub>2</sub> production processes for steel production in greenfield production facilities.				
Process	TRL Status	CO <sub>2</sub> Emissions, Tonne CO <sub>2</sub> /Tonne Steel	Capital Expenses, €/Tonne	References
<i>Primary steel production</i>				
Blast furnace with basic oxygen furnace (BF/BOF)	Commercial (TRL 9)	1.6–2.2	386–442	[15,16]
Top gas recycling blast furnace (TGRBF/BOF)	TRL 7	1.44–1.98	632	[17–19]
CO <sub>2</sub> capture technology <sup>1</sup>	TRL 6–9	CO <sub>2</sub> capture efficiency (%): 90	25–85	[17,20–23]
Smelting reduction (SR/BOF)	Commercial (TRL 9)	1.2–2.25	393	[15,21]
Direct reduction using electric arc furnace (DR/EAF)	Commercial (TRL 9)	0.63–1.15	414	[15,18,24]
Hydrogen direct reduction using electric arc furnace (H-DR/EAF)	TRL 1–4	0.025	550–900	[25–27]
Electrowinning (EW)	TRL 4–5	0.2–0.29	639	[9,25,28]
<i>Secondary steel production</i>				
Electric arc furnace (EAF)	Commercial (TRL 9)	0.6	169–184	[15,29,30]
Electric arc furnace/biomass (EAF/biomass)	TRL 6–8	0.005	169–184	[26,31]

<sup>1</sup> Capture emission points: BF, TGRBF.

**Table 6.1.** Commercially available low CO<sub>2</sub> emission production processes

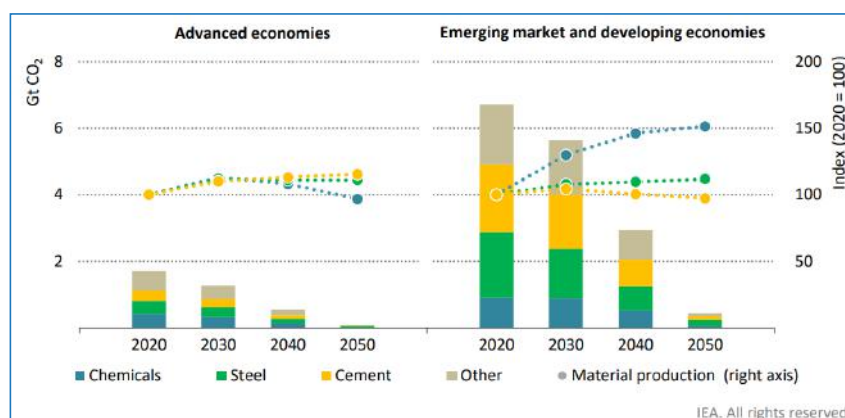
Source: Toktarova et al (2020)<sup>21</sup>

<https://www.mdpi.com/1996-1073/13/15/3840>

Besides the routes already considered, *Table 6.1.* includes the top gas recycling blast furnace that relies on removing the CO<sub>2</sub> from the top gas and reinjecting the remaining gas to the blast furnace, and biomass-derived fuels as a means to reducing CO<sub>2</sub> emissions. Biomass may replace fossil fuels in sintering or pelletising, substituting coke or pulverised coal injected; the respective substitution rates of biomass for the above depend on the considered applications. Also included is the deployment of carbon capture technology, considering the integration of post-combustion capture can reduce (capture) carbon dioxide emissions from existing plants without major modifications.

### 2.5.3. Contribution of the steel industry to net-zero emissions

As is well known, the objective of net-zero emissions for 2050, or 2060 depending on the countries and regions is a scenario several institutions are analysing. The IEA report Net Zero by 2050<sup>22</sup> raises an interesting discussion about energy and emission trends in the Net-Zero Emissions Scenario. In *Fig. 6.15.* below, the IEA indicates a dramatic decline in CO<sub>2</sub> emissions from the emerging market and developing economies, especially China. At the same time, steel production volumes would be relatively flat up to 2050.



**Fig. 6.15.** Global CO<sub>2</sub> emission reduction scenarios from industry by sub-sector in the NZE  
IEA Net Zero by 2050 A Roadmap for the Global Energy Sector (Figure 3.15, Page 122)  
*Net Zero by 2050 - A Roadmap for the Global Energy Sector* (windows.net)

<sup>21</sup> Toktarova, A. Karlsson, I., Rootzen, J. Goransson, L. Odenberger, M. and Johnsson (2020). "Pathways for low- carbon transition of the steel Industry. A Swedish case" *Energies* 2020, 13,3840

<sup>22</sup> Released May 2021 ([Net Zero by 2050 – Analysis - IEA](#))

In the same report, figures are provided for the projection of CO<sub>2</sub> emissions from the steel industry (and other industries): these would drop, from around 2 350 Mt in year 2020, to 1 800 Mt in year 2030, 850 Mt in year 2040 and 200 Mt in year 2050. This is equivalent to an annual decline of about 2.7% between 2020 and 2030 and as much as 7.6% between 2020 and 2050.

Given the weight of China in terms of steel production and related CO<sub>2</sub> emissions, the IEA has also analysed the situation and trends of them. Indeed, according to another recent report by the IEA (An Energy Sector Roadmap to Carbon Neutrality in China, IEA, 2021<sup>23</sup>), CO<sub>2</sub> emissions from China's iron and steel industry would decline from around 1.5 Gt in 2020 to 1.4Gt in 2030 and around 120 Mt by 2060 in the APS (Announced Pledges Scenario).

Material and energy efficiency measures, largely associated with the increased use of scrap steel, account for around 50% of the cumulative emission reductions to 2060. The increase in scrap use is driven in large part by economic factors and would occur regardless of efforts to cut emissions.

In the longer term, as with the other heavy industrial sectors, the burden of reducing emissions falls to the deployment of innovative technologies that are not commercially available today, primarily CCUS and electrolytic hydrogen, which together account for around 15% of the cumulative emission reductions. They are associated with two main production routes: hydrogen-based direct reduced iron (DRI), a relatively energy-efficient process that may in the future be directly twinned with low-cost, captive variable low-carbon sources-based electricity production; and the innovative smelting reduction process, which avoids the need for a coke oven and some agglomeration processes, thus producing a purer CO<sub>2</sub> stream that is more amenable to capture.

Together, these routes account for more than two-thirds of primary steel production by 2060, with most of the remainder being supplied by conventional blast furnaces nearing the end of their lives. Scrap-based electric arc furnace production accounts for more than half of total steel production by 2060<sup>24</sup>.

#### 2.5.4. Mining

Tost, M. et al. (2018)<sup>25</sup> estimate the global CO<sub>2</sub> emissions of iron ore mining in 2016 to be 38.3 Mt and 11.9 kg CO<sub>2</sub>/t of iron ore. A similar result is provided by Skarn Associates, which estimates at 34 Mt of CO<sub>2e</sub> the emissions of the scope 1 and 2 of iron ore, excluding China, and calculates 62 Mt of CO<sub>2</sub> were emitted for freight and downstream. (See Fig. 6.16.)

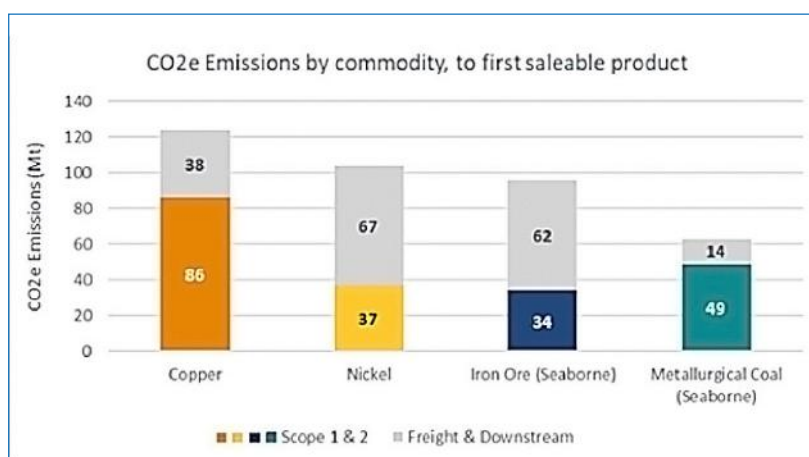


Fig. 6.16. CO<sub>2</sub> Emissions by commodity to first saleable product

Skarn Associates, Carbon emission curves for iron ore, copper, metal coal and nickel

<https://www.mining.com/carbon-emission-curves-for-iron-ore-copper-met-coal-and-nickel/>

<sup>23</sup> [An energy sector roadmap to carbon neutrality in China Title of the Report \(windows.net\)](#) (page 109)

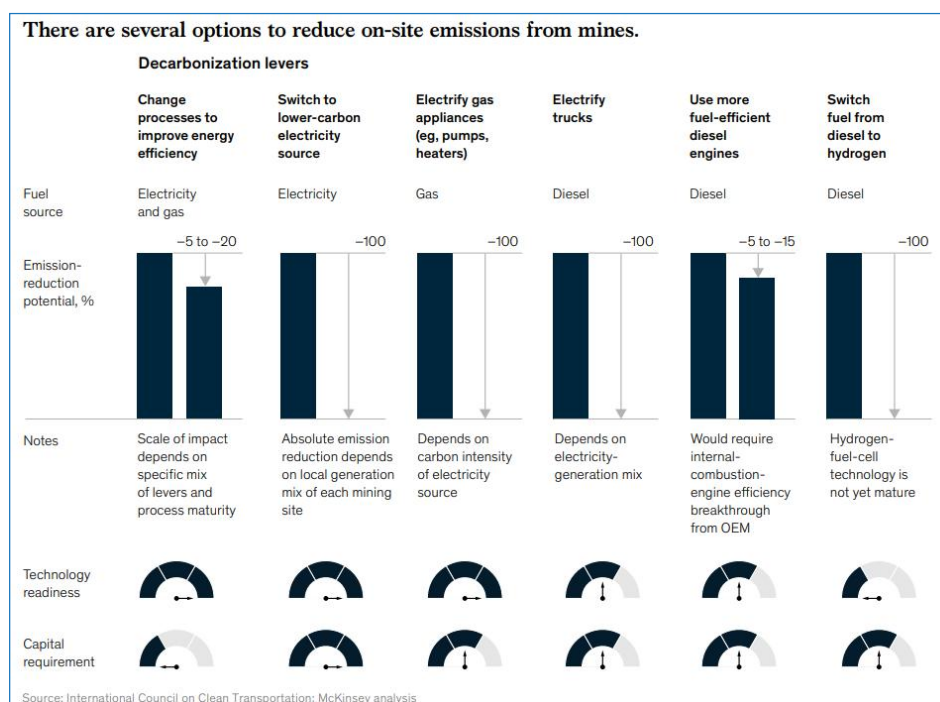
<sup>24</sup> Toktarova, A. Karlsson, I., Rootzen, J. Goransson, L. Odenberger, M. and Johnsson (2020). "Pathways for low- carbon transition of the steel Industry. A Swedish case" Energies 2020, 13,3840

<sup>25</sup> Tost, M. Bayer, B. Hitch, M. Lutter, S. Moser, P. and Feiel, S. (2018) "Metal Mining's environmental Pressures, A Review and Updated Estimates on CO<sub>2</sub> Emissions, Water Use, and Land Requirements" Sustainability 2018,10, 2881

“The mining industry generates between 1.9 and 5.1 gigatonnes of CO<sub>2</sub> equivalent (CO<sub>2e</sub>) of GHG annually. The majority of the emissions in the sector originate from fugitive coal-bed methane that is released during coal mining (1.5 to 4.6 gigatonnes) mainly in underground operations. Power consumption in the mining industry contributes 0.4 gigatonnes of CO<sub>2e</sub>.”

Further down the value chain – what could be considered Scope 3 emissions – the metal industry contributes roughly 4.2 gigatonnes, mainly through steel and aluminum production”<sup>26</sup>.

Most of the greenhouse gas emissions in mining are generated in downstream industries (scope 3) and during coal mining (fugitive methane). According to McKinsey (2020), there are several options to reduce on-site emissions from mines, as illustrated in the figure below.



**Fig. 6.17.** Options for reducing on-site emissions from mining operations

Exhibit from “Climate risk and decarbonization: What every mining CEO needs to know”, January 2020, McKinsey & Company, [www.mckinsey.com](http://www.mckinsey.com). Copyright (c) 2022 McKinsey & Company. All rights reserved. Reprinted by permission.

[Climate risk and decarbonization: What every mining CEO needs to know | McKinsey](#)

As may be seen, the electrification of the operations will be key: green power (low-carbon energy) will be supplied by the grid or self-generated, and for the vehicles (dump trucks, haul trucks, etc.), diesel will be replaced by low-carbon (or net-zero) fuel. In any case, improvements in efficiency should be a must.

Currently there are two options to power a mining complex. If the grid is available in the vicinity, the mine is directly connected to the grid. In the absence of grid connection (remote location), on the other hand, a local heavy fuel oil power plant is used to generate electricity. The cost of fuel supply is a significant contributor to OPEX.

In the case of off-grid mines, the deployment of a micro-grid would typically be powered by solar radiation or wind. These are intermittent sources that will therefore require energy to be stored at large scale and over a long period of time (e.g. in northern mines). For this type of storage, one option is to store energy in a chemical form. This is where hydrogen or hydrogen compounds may play a role<sup>27</sup>.

Regarding the storage of energy, pure hydrogen may not be the best solution (small molecule, safety regulations, etc.). Depending on local conditions, rock cavern storage may be a solution and is under development (see for

<sup>26</sup> “Climate risk and decarbonization: What every mining CEO needs to Know” (2020) McKinsey

<sup>27</sup> Another option may emerge in the form of modular mini-nuclear power plants (SMRs). Long-term storage is then less critical.

example the HYBRIT project, *Section 6.*). In other cases, it might be better to use a hydrogenated molecule such as methanol or DME, Dimethyl Ether, (which can be manufactured on site with hydrogen and captured CO<sub>2</sub>) or ammonia (assuming a source of nitrogen is available or obtained by air separation). The other advantage of hydrogen is that it may be used for vehicles. Indeed, DME and ammonia are also fuels that may serve in engines as replacements for diesel. These technologies already exist. The present challenges are therefore related to costs and deployment issues at the mining scale (particularly the availability of large equipment).

In a mining complex, in general, the following two types of energy are relevant.

- Electricity for operations. The most consuming operations are related to comminution (crushing, grinding), the dewatering of the mine and subsurface ventilation for underground mining. Electricity should be available 24/7.
- Diesel fuel<sup>28</sup> used in vehicles (haul trucks, excavators, drills, loaders, dozers) and machinery, including power gensets and other applications.

Kumar Katta, A. et al. (2019)<sup>29</sup> analyse the energy use and greenhouse emissions footprints of several types of mines in Canada. The situation for the iron ore mines is reflected in the figure below.

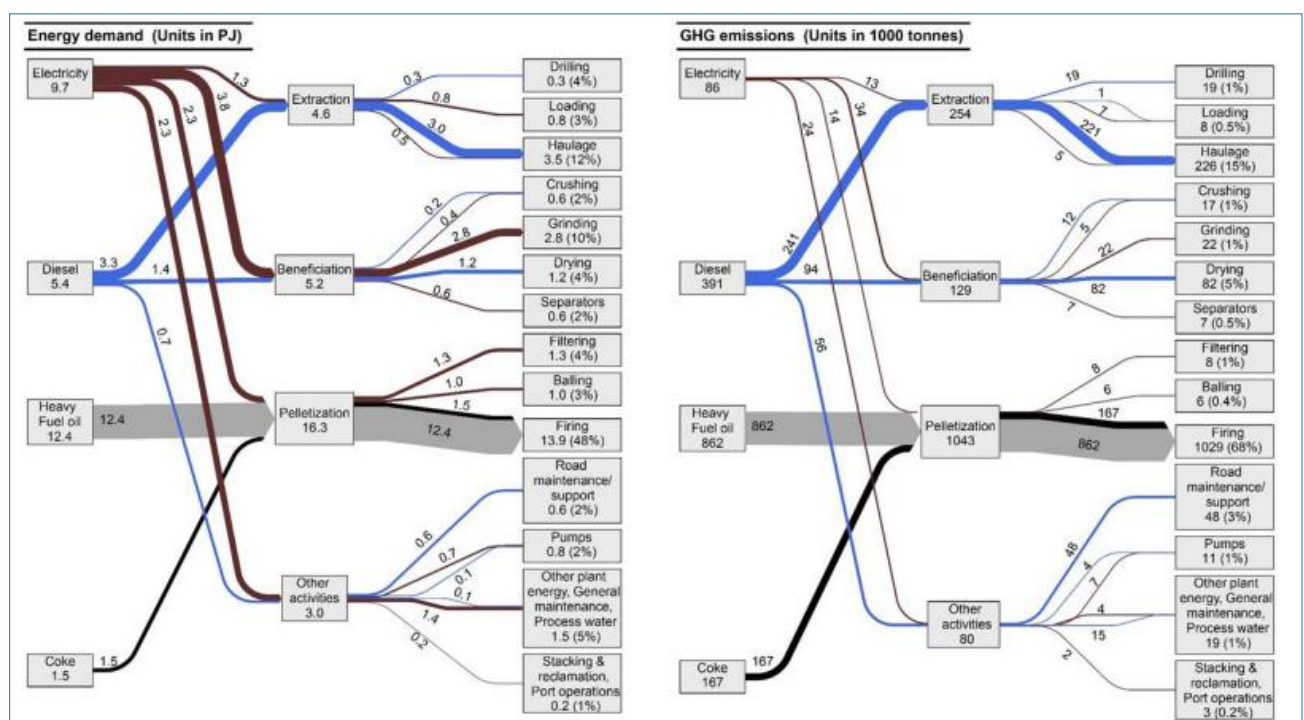


Fig. 6.18. Sankey diagram for Canada's iron mining energy demand (left) and GHG emission (right) in 2015

In terms of energy, heavy fuel oil (12.4 PJ, or 3.44 TWh) and electricity, (9.7 PJ, or 2.69 TWh) are the most used sources of energy, followed by diesel (5.4 PJ, or 1.5 TWh), while coke (1.5 PJ, or 0.42 TWh) has a minor use. The authors argue that the first step in understanding the potential for decarbonisation is to identify how energy is now being used, in what form, and what the associated GHG emissions are.

### 3. Existing, forthcoming and possible breakthrough solutions

#### 3.1. Introduction to decarbonisation technologies

As mentioned in *Section 2.*, there are at present two main manufacturing methodologies for steelmaking. These methodologies use either the Integrated Blast Furnace BF / BOF processing route, which converts virgin

<sup>28</sup> Furthermore, in iron ore mining, diesel consumption dominates in hematite processing, whereas it is roughly equivalent to electricity consumption in magnetite processing, which requires more processing and concentration due to its lower content in iron oxide (Engeco 2021). Mining Energy Consumption 2021.

<sup>29</sup> Anil Kumar Katta, Thesis, Assessment of Greenhouse Gas Reduction Options for the Iron, Gold, and Potash Mining Sectors, 2019, Department of Mechanical Engineering University of Alberta, Page 48  
[https://era.library.ualberta.ca/items/94af642f-b70b-4fbb-af36-5be47b870288/view/fd211268-7381-4120-af73-c33a6d8038a4/Katta\\_Anil\\_K\\_201907\\_MSc.pdf](https://era.library.ualberta.ca/items/94af642f-b70b-4fbb-af36-5be47b870288/view/fd211268-7381-4120-af73-c33a6d8038a4/Katta_Anil_K_201907_MSc.pdf)

raw materials into liquid steel, or the electric arc, which melts steel scrap alongside a range of other ferrous bearing materials.

The dominating part (around 85%) of CO<sub>2</sub> emissions result from the use of coal or natural gas in the reduction processes that take place in the blast furnaces. Measures and actions are continuously going on to reduce the climate impacts of such *existing and running* processes. Both methodologies have strengths and weaknesses built into the investment model for the manufacturing site, with investment cycles for new technologies and processes lasting throughout the lifespan of the site, which can often be measured in decades.

Section 2. has reflected on some of the optimisation methodologies BF / BOF (Blast Furnace / Basic Oxygen Furnace) steelmakers are using, innovative existing BF / BOF processes and some potential high-interest future technologies. Reducing or eliminating greenhouse gas-emitting fuels, however, will be possible through new technologies described as *forthcoming and breakthrough solutions*. Globally, the route to decreasing emissions is likely to be a transitional one, regional interests, geographical and local conditions, and technological availability being the limiting factors that impede the rate of progress.

McKinsey has compared the potential technology pathways for existing and forthcoming solutions, which are presented in the following table<sup>30</sup>.

	Strategy	Examples	Current Outlook
<b>BF / BOF Efficiency Programmes</b>	Make efficiency improvements to optimise BF / BOF operations	Increased Scrap in BOF, Scrap Charging in BF, Fuel Changing in BF	Technology readily available, often extensive retrofitting
<b>Biomass Reductants</b>	Use biomass as alternative fuel source	Tecnored process	Available in localised regions where biomass is available – South America & Russia
<b>Carbon Capture &amp; Usage</b>	Capture CO <sub>2</sub> emissions and create new products	Bioethanol production from CO <sub>2</sub> emissions	Yet to be proven at industrial scale within steel industry. Some examples within Cement.
<b>Electric Arc</b>	Maximise recycling via EAF	EAF used to melt scrap	Technology available at scale
<b>DRI &amp; Electric Arc manufactured by NG</b>	Replace some scrap with DRI	DRI plants already utilise NG	Technology available at scale
<b>DRI manufactured by Hydrogen in EAF</b>	Replace NG in DRI process with Hydrogen	Midrex Process running on Hydrogen HYBRIT process running on Hydrogen	High-cost technology requiring significant investment in both Hydrogen generation & DRI capacity

**Table 6.2.** Potential technology pathways for existing and forthcoming solutions

## 3.2. Existing technologies

### 3.2.1. Making the most of recycled raw materials: the example of scrap

Steelmaking based on the EAF (Electric Arc Furnace) emits 50-75% less CO<sub>2</sub> emissions than traditional BF / BOF steelmaking, as described in Section 2.. Maximising the use of secondary steel and the recycling of raw material appears to be an important way to decarbonise the steelmaking industry.

Section 2. explains the use of BFs / BOFs accounts for around 2/3 and EAFs for 1/3 of global steelmaking. Yet, there are large differences from region to region. China, for example, has almost 90% BOF steel, while the United States of America has around 30%. In the EU, only about 40% steel today is made via the EAF and 60% via the BF / BOF.

The Joint Research Centre of the EU Commission published in 2022 “Technologies to decarbonize the EU steel industry”. Below is one of its key conclusions concerning recycling and EAF.

“Steel is a highly circular material – some 85% of end-of-life steel is recycled, emitting only a fraction of the CO<sub>2</sub> of new primary steel. Maximising the share of recycled steel is an important lever to reduce CO<sub>2</sub> emissions. However, due to limits in quality, old scrap is mostly downcycled to lower quality steel and significant demand for primary steel will persist in the future<sup>31</sup>.”

<sup>30</sup> Exhibit from “Decarbonization challenge for steel”, June 2020, McKinsey & Company, [www.mckinsey.com](https://www.mckinsey.com). Copyright (c) 2022 McKinsey & Company. All rights reserved. Reprinted by permission. - <https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel>

<sup>31</sup> JRC Publications Repository - Technologies to decarbonise the EU steel industry ([europe.eu](https://europe.eu))

China, the first steel producer in the world, has declared that it aims to “significantly increase” mine iron ore production and boost the utilisation of steel scrap, as part of a plan to develop a higher-quality and greener ferrous industry.

The statement, made by the Ministry of Industry and Information Technology (MIIT), was that more than 80% of steel capacity should complete ultra-low emissions reform by 2025, and the carbon emissions of the industry should peak before 2030. By 2025, China aims to be gathering over 300 million tonnes of steel scrap annually to supply its ferrous industry. A government-backed consultancy estimated steel scrap supplies stood at around 260 million tonnes in 2020<sup>32</sup>.

### 3.2.2. Improving the efficient collection and sorting of scrap

Increasing the share of scrap input requires efforts in increasing the quality of end-of-life scrap, by improving the dismantling and sorting of end-of-life products or designing products with end-of-life dismantling and material recuperation in mind (Daehn et al., 2017).

In external decarbonization scenarios, e.g. using low-carbon electricity, where the potential to increase scrap quality is maximized and overall steel demand is reduced, the share of scrap steel inputs used in EU steelmaking could increase from the current 50% to 60% (IEA, 2020) or even 70% in high recycling scenarios (Fleiter et al., 2019; Material Economics, 2019). An interesting comparison to the EU is the case of the USA, where 70% of steel is made in EAFs, including significant amounts of higher-quality flat steel. Some of the factors explaining how USA steel manufacturers can produce high-quality steel in EAF are the deployment of modern mini-mills in the USA with better EAF technology, the use of high-quality prime steel scrap (over recycled shredded scrap) and the addition of metallic raw materials such as pig iron from blast furnaces and direct-reduced iron to ‘sweeten’ the EAF input and dilute impurities (S&P Global Platts, 2019).

In Korea, for example, one key measure is the use of technology to abate indirect CO<sub>2</sub> emissions by reducing electric power consumption through decreasing energy consumption and / or operation time. The substitution of injected carbon (C), for carburising and slag forming, with less carbon-intensive sources such as waste plastics, waste tires, biomass, etc. is under development

### 3.2.3. Optimising the whole transport system and methods including the use of low-carbon or low carbon fuels for transport

Among the measures supporting energy efficiency and the reduction of greenhouse gas emissions, internal transport appears to be a common and to some extent new trend. The driving forces have been at the same time improving the work environment, fostering efficiency, and partly reducing the carbon dioxide emissions of the business. Companies have taken action through electrifying and, to a greater extent, switching to biofuels. These emissions are small in relation to those of steel production, but it is nevertheless worth highlighting such measures, not least as a sign that companies are reviewing their entire operations and taking responsibility by implementing real changes. New technologies for heavier vehicles and the possibility of fast charging electric vehicles are crucial. Examples include: - the electrification of heavy trucks by electric trolley lines<sup>33</sup>, and - the automation and electrification of transport<sup>34</sup>.

### 3.2.4. Electrification of heating and heat-treatment processes

Electrification is a solution to replace the use of fossil fuels in heating and heat treatment. Such opportunity is greatest when heat processing takes place at temperatures below 1 000 °C. In recent years, both heating and heat treatment furnaces have been electrified at several steel companies and this work continues. Electrification has been accomplished through the conversion of existing furnaces that were previously powered by propane (or other fossil fuels like natural gas or coke oven gas). The cost of the investment is estimated to be repaid within less than three years (depending on electricity prices), through lower operating costs, reduced maintenance, and fewer disruptions.

<sup>32</sup> Reuters News 2022-02-07 [UPDATE 1-China plans to increase iron ore output, boost use of steel scrap | Reuters](#)

<sup>33</sup> <https://www.boliden.com/sustainability/case-studies/climate-smart>

<sup>34</sup> <https://www.lkab.com/en/news-room/news/sjalvkorande-fordon-elektrifiering-och-automation-med-manniskan-i-centrum/> (Autonomous vehicles, electrification and automation with a focus on people (lkab.com))

### 3.2.5. Bio-based gas and low-carbon hydrogen as substitute for fossil fuels in heating and heat-treatment processes.

Bio-based gas or hydrogen can replace fossil fuels in processes that cannot be electrified. This requires adequate access to stable quality gas equivalent to natural gas and LPG. The costs of gas should also be competitive as regards international energy costs.

Hydrogen produced from electrolysis through low-carbon electricity can be used in heat treatment processes as a step towards climate-neutral steel manufacturing.

OVAKO Steel in Sweden provides an example of such use. Full-scale trials in a production environment showed that heating steel with hydrogen does not affect quality. An electrolyser to produce low-carbon hydrogen will be installed at Ovako's site in Hofors and is expected to be completed by the end of 2022<sup>35</sup>.

### 3.3. Technologies in progress

This section aims to describe decarbonisation processes that have reached the stage of pilot and demonstration-scale and will be in commercial operation in the coming years or are already in commercial operation at small scale.

#### 3.3.1. Direct reduction of iron ore by hydrogen in shaft furnace

The direct reduction of iron ore using natural gas or coal is already a well-established technology, with 111 million tonnes of DRI produced globally in 2019 (World Steel Association, 2019). DRI (sponge iron) is then processed to steel in an EAF. At present, various types of DRI technology are deployed. Using hydrogen for the direct reduction of iron ore to iron (HDRI) completely avoids employing fossil fuels.

- Technology and processes step by step: iron ore pellets, direct reduction to sponge iron, electric arc melting, hydrogen electrolyser

A simplified process diagram is presented in the technical report of the European Commission Joint Research Centre "Technologies to Decarbonize the EU Steel Industry"<sup>36</sup>.

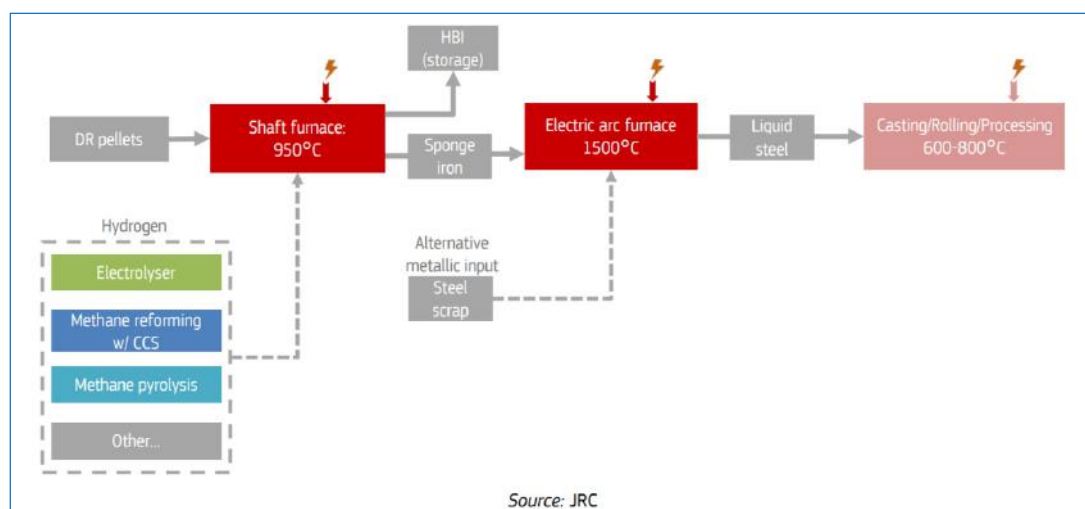


Fig. 6.19. Simplified flow diagram of the hydrogen DRI process

Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-47147-9 (online), doi:10.2760/069150 (online), JRC127468, Page 24

Depending on the source of the hydrogen used, this technology offers potential to produce truly green steel. Hydrogen-based DRI is therefore expected to be a major decarbonisation lever for steelmakers, particularly in Europe.

A detailed description of the process is presented by the World Steel Association in a Fact Sheet.

- Potential emission decrease and results

<sup>35</sup> <https://www.ovako.com/en/newsevents/stories/first-in-the-world-to-heat-steel-using-hydrogen/>

<sup>36</sup> <https://publications.jrc.ec.europa.eu/repository/handle/JRC127468>

CO<sub>2</sub> emissions average around 1.85 tonnes of carbon dioxide per tonne of steel produced (World 2020, Steel Association<sup>37</sup>). Using hydrogen electrolysis from low-carbon-electricity, the Hydrogen DRI process will make it possible to increasingly produce low-carbon steel.

A calculation of CO<sub>2</sub> emissions and energy demand per tonne of crude steel produced has been presented for the implementation on an industrial scale of the HYBRIT technology now under development. This process, using low-carbon electricity, is expected to produce fossil emissions in the order of 0.025 tonnes per tonne steel produced<sup>38</sup>.

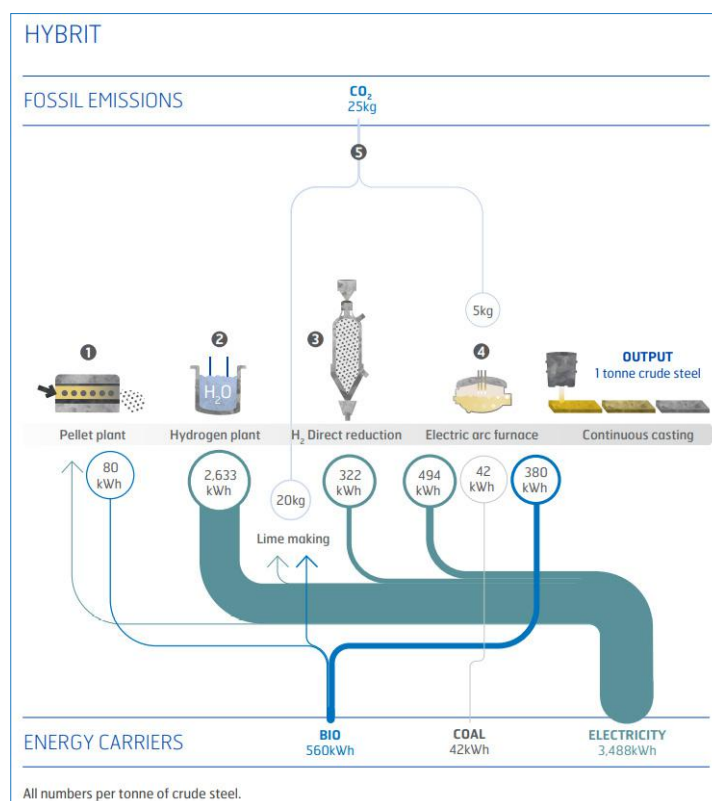


Fig. 6.20. CO<sub>2</sub> emissions using HYBRIT technology

- Preconditions, iron ore access and quality, electricity demand (low-carbon), hydrogen storage – Identified challenges

The quality of the DRI is closely related to that of iron ore inputs. DRI is thus mostly made from very high-quality raw materials, which can be produced at only a limited number of mines. However, mining companies in general have the possibility to upgrade lower grade iron ore to higher grade iron ore pellets, or even make and export the hydrogen DRI on site if low-carbon electricity is available.

Electricity demand and transmission from low-carbon sources to the future production sites play an important role in securing the foreseen increased demand for electricity.

Low-carbon electricity will probably be hydropower, wind-power, solar power, or nuclear power, depending on local conditions. Transmission lines could be an obstacle, depending on existing infrastructures and permission conditions. Electricity generation costs will be crucial for overall competitiveness.

Hydrogen production will be based on existing commercial technology, yet to be proven on a large scale. Hydrogen storage plays a major role in the economics and integration of value chains, as a means to secure reliable production, and especially so if the generation of electricity is to a great extent dependent on wind and solar power. Technologies for large-scale hydrogen storage are still untested.

<sup>37</sup> <https://worldsteel.org/publications/policy-papers/climate-change-policy-paper/>

<sup>38</sup> [Hybrit-broschure-engelska.pdf \(dh5k8ug1gwbyz.cloudfront.net\)](#), page 16

The challenges will be described in more details in *Section 5.*

### 3.3.2. Direct reduction of iron ore by hydrogen in fluidised bed reactor

The Korean ‘Carbon-neutral industrial core technology development project’ prepares five key areas for carbon-neutral value chains. One of them concerns new technology for primary steelmaking. Instead of conventional blast furnace operations and converters, fluidised bed reactors are utilised to produce HDRI directly connected with SAF / EAF combinations.

Developments in hydrogen reduction fluidised bed reactor technology to produce direct reduced iron are underway. Greater experience and operational know-how are necessary to develop direct hot charging into the EAF to melt HDRI. Quality issues may arise due to the low carbon content of the hot metal; it would thus be necessary to separate refining and clean steel technology developments in order to customise the manufacture of the high-grade steels necessary for downstream customers.

### 3.3.3. Bio-coke injection in Blast furnaces (BF / BFO)

The blast furnace (BF / BFO) process is an extremely energy-efficient one that has been developed over a long period of time. Thus, only very limited efficiency gains are left in the process to reduce carbon dioxide emissions. As BF processes are the dominant ones, and as investments to replace them with direct reduction (DRI) are huge, alternative measures to reduce emissions from the existing blast furnaces are interesting and underway.

Biomass as a blast furnace injectant has been studied and tested, in particular by the Luleå University of Technology, in cooperation with the Swedish steel industry. In the study, the considered biomass was either pelletised, torrefied or pyrolysed. Charcoal from pyrolysis was found the most efficient resource and can fully replace pulverised coal, while the replacement rates applying to torrefied material and pelletised wood are 22.8% and 20.0% respectively, by weight. Leaving aside the reduction in CO<sub>2</sub> emissions, substantial energy savings were found<sup>39</sup>.

### 3.3.4. Bio-coke for the reduction of iron ore in powder production

Developing bio-coke to reduce iron ore for steel powder production requires adequate access to biomass and suitable by-product carbonisation processes for bio-coke production and at a cost equal to that of fossil coke.

Such technology is based on the gasification and restructuring of forestry biomass to a low-carbon synthesis energy gas and bio-coke. The energy gas will replace natural gas in metal powder production.

A unique pilot-scale test production has been in operation since 2021 at Höganäs AB, in the south of Sweden<sup>40</sup>.

## 3.4. Need for further R&D for breakthrough solutions

The breakthrough technologies needed to decarbonise primary steel production are the results of decades of R&D in the sector. Still further R&D investments for the pilot, demonstration and first-of-a-kind commercial plants are needed.

The European Commission has been supporting early-stage R&D projects in the steel sector in the past. Several of the key decarbonisation technologies being considered by the steel industry were developed via different EU funding programmes. Similar research programmes and funding are ongoing in the America and Asia regions.

A broad bibliometric search of scientific papers provides some insight into which regions of the world have been most active in research supporting low-CO<sub>2</sub> steel manufacturing. General terms such as ‘green steel’, ‘low-carbon steel’ and steel decarbonization’ were searched for in the years 2000 to 2020. This analysis of publication activity shows the European Union (EU-27) leading the field, spearheaded by German and more recently Swedish publications, with steep increase since 2010. China shows similar levels and a similar trajectory of research activity to those of the EU, while the remaining countries have not followed such sharp increase in research output<sup>41</sup>.

<sup>39</sup> Biomass as blast furnace injectant “Considering availability, pre-treatment and deployment in the Swedish steel industry (diva-portal.org) <http://kth.diva-portal.org/smash/get/diva2:806989/FULLTEXT01.pdf>

<sup>40</sup> Ref: [Unique plant for renewable energy gas and bio-coke | Höganäs \(hoganas.com\)](https://www.hoganas.com/en/unique-plant-for-renewable-energy-gas-and-bio-coke)

<sup>41</sup> JRC Publications Repository - Technologies to decarbonise the EU steel industry (europa.eu), pp. 36-37 <https://publications.jrc.ec.europa.eu/repository/handle/JRC127468>

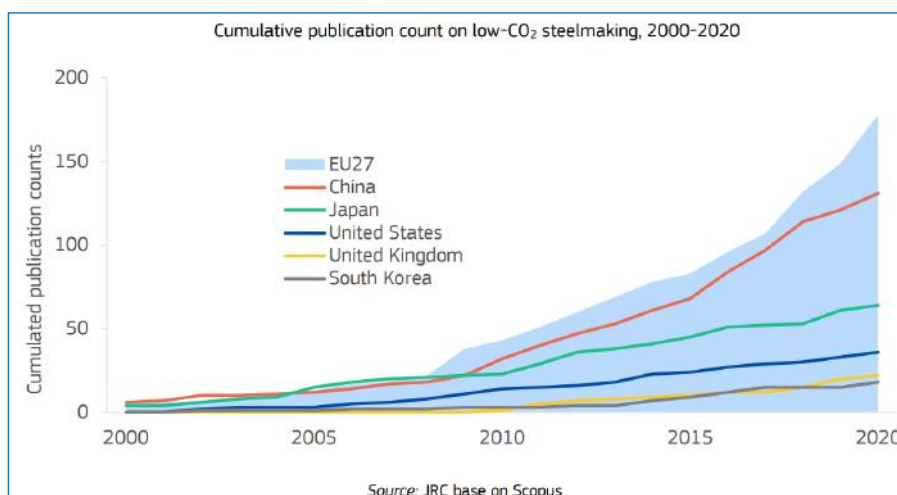


Fig. 6.21. Cumulative publication count on low-CO<sub>2</sub> steelmaking, 2000-2020

In Korea, the COOLSTAR project (CO<sub>2</sub> Low-emission-technology of Steelmaking and hydrogen Reduction) has been underway since 2017. The initial goal of this project was to increase the use of hydrogen-containing gas instead of coal and coke input into the blast furnace. Both the utilisation of hydrogen and partial replacement of coal with carbon-neutral reducing agents, such as hydrogen-containing resources or biomass, were expected to lower CO<sub>2</sub> emissions by 10%.

## 4. Recycling: scrap metal combined with direct reduction or arc furnaces

### 4.1. Overview

Steel scrap is one of the major iron sources in the steelmaking process along with pig iron (produced in the blast furnace) and direct reduced iron (DRI). While the EAF mostly utilises steel scrap, the integrated steel route with the BOF uses approximately between 15 to 20% of scrap – for reducing carbon emissions an increasing production capacity-, with pig iron as the balance. Every tonne of scrap used for steel production avoids around 1.5 tonnes of CO<sub>2</sub> emissions along with a decrease in the consumption of 1.4 tonnes of iron ore, 740 kg of coal and 120 kg of limestone.

Since steel scrap represents metallic iron units generated during the earlier chemical reduction of iron ore (oxide), both the energy and carbon typically required for ore reduction in the integrated steel route are avoided, which may reduce the carbon dioxide emitted in the integrated steel route by as much as 35%. Globally, steel production in 2020 reached approximately 1.9 billion tonnes (Bt) with 1.3 Bt (68.3%) produced through the integrated route and 0.6 Bt through the EAF route, as shown in *Table 6.3.* If scrap input in the integrated steel route with the BOF comprises roughly 15% of the mass input and the EAF utilises 100% scrap, then one may expect approximately 0.89 Bt of scrap were used in the production of steels; the steel industry thus avoided roughly 1.3 Bt of CO<sub>2</sub> emissions in 2020 by employing scrap. Even greater scrap utilisation is possible by increasing the proportion of EAF steelmaking, and by making changes in the integrated iron and steelmaking processes, while recycling systems and scrap collection at end-of-life are also important in any considerations of increased scrap utilisation.

Item	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Steel production	1 435 254	1 539 861	1 562 332	1 652 329	1 674 003	1 625 141	1 632 780	1 735 875	1 825 486	1 875 155
BF-BOF	993 374	1 065 079	1 099 079	1 209 799	1 224 934	1 202 651	1 199 777	1 206 963	1 291 274	1 340 985
EAF	421 750	454 198	448 349	419 947	434 459	407 105	417 719	471 778	524 303	523 142
Production-Pig Iron	1 034 337	1 103 856	1 123 042	1 170 091	1 187 040	1 160 530	1 173 520	1 186 136	1 252 767	1 281 998
Production-DRI	72 019	76 725	76 879	79 616	82 268	75 982	77 848	92 227	106 807	111 052

**Table 6.3.** Steel production by process route after statistical data from the World Steel Association (Unit: thousand tonne).

<https://worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook/>

It is well known that the quality of recycled ferrous scrap is a key factor in determining the final product quality and energy efficiency in the electric arc furnace process. The character of ferrous scrap is determined by its physical shape, which varies depending on the source, and its chemical composition. Scrap may contain impurities from end-of-life recycling processes (like copper wiring from automobiles), alloying elements added to the particular steels being recycled (or coatings), and recirculating tramp elements that are difficult to remove from the steel. Some important impurities include elements such as copper (Cu), tin (Sn), nickel (Ni), chromium (Cr), arsenic (As), antimony (Sb), etc.

While some impurity elements are easily separated from the iron after remelting, as they are oxidised and enriched in the slag, the critically important tramp elements are not readily removed with existing processes. The thermodynamics are not favourable for redistribution into the slag phase from the metal phase for these critical tramp elements. Thus, an additional high-quality iron source containing a lower tramp element concentration must be used to dilute the steel, depending on the product / application requirements for the particular steel being manufactured. Some of these so-called prime iron sources include not only high-grade scrap but also 'fresh iron units', including DRI (direct reduced iron) and pig iron.

Table 6.4. below shows typical concentrations of tramp elements contained in different steel product forms after the product life span. It should be noted that the levels and tolerance for these tramp elements is different in different countries, and both the process used when recycling ferrous scrap and the utilisation of alternative iron sources such as DRI and pig iron may alter the tolerance. Copper and tin residuals can have important detrimental effects in the hot-rolling of steels. A typical copper limit in recycled steel production is approximately 0.2% by mass. A general perspective on the level of tramp elements for plate products for integrated steel production using the blast furnace and converter, is an approximate range of Cu < 0.06~0.1% and Sn < 0.01~0.02%. For crude steel production in the electric furnace process, more typical ranges are Cu < 0.18~0.3% and Sn < 0.03~0.08%.

Product type	Average elemental concentration (mass pct)				
	Cu	Sn	Cr	Ni	Mo
Rail	0.165	0.000	0.215	0.063	0.021
Section	0.176	0.003	0.109	0.055	0.016
Bar	0.269	0.015	0.175	0.078	0.014
Pipe	0.013	0.000	0.010	0.010	0.001

**Table 6.4.** Average mass percentage of the major recirculating tramp elements per steel products (Units: mass percentage).

Reference: Daigo et al., ISIJ Int., 2017, Vol.57, pp.388.

Both global supply and demand of ferrous scrap have been continuously increasing since 1999, but declined sharply in 2015. However, due to the recent tightening of environmental regulations with CO<sub>2</sub> emissions in the steel industry, electric arc furnace production has significantly increased and subsequently scrap trade volume is once again increasing. This will also be compounded as the BF-BOF integrated steel route begins to shift

towards higher scrap utilisation processing with scrap to hot metal ratios increasing up to 30% by mass from the typical average of 15% by mass. This significant impact on the scrap supply will likely put pressure on the availability of high-grade steel scrap and the price of scrap in the global market. While there is global trade in steel scrap, scrap collection is localised and decentralised, with processes, economics and regulations that vary geographically.

Ferrous scrap may be classified into self-generated internal scrap, prompt scrap, and obsolete scrap, according to the location of the scrap generated and its source. Self-generated internal scrap also identified as home scrap or revert scrap is generated in the steel process itself and has the same components as the semi-finished steel products; it is thus typically re-used within the primary steelmaking process itself. Prompt scrap or process scrap is defined as scrap generated during end-product manufacturing by the steel plant's customers. Prompt scrap is classified as a clean iron source because the content of recirculating tramp elements that are difficult to separate and refine is comparatively low. Finally, obsolete scrap represents the consumer products that have fulfilled their intended purposes — used beverage or aerosol cans, old auto parts, construction waste and disposed home appliances, etc. Obsolete scrap is variable in shape and composition due to its unspecified use, origin, and history. Home and prompt scrap can typically be returned to the steelmaking process with little or no pre-treatment, while the obsolete scrap may require significant harvesting of the ferrous source to remove the impurities and tramp metal elements. Obsolete scrap is much more plentiful than home scrap or prompt scrap, but due to the aforementioned impurities including the tramp elements in the product, it may be usable in fewer applications where scrap quality requirements are less critical. Obsolete scrap requires significant time to obtain, process, and return to the steel producers. With a more developed steel-intensive economy, the availability of obsolete scrap becomes greater. Pre-treatment processes may enable obsolete scrap to be upgraded.

## 4.2. Current status of iron scrap trade, supply and specifications

### 4.2.1. Current status of global ferrous scrap trade and supply

Trade statistics for ferrous scrap were obtained from the World Bank's world integrated trade solution and include a variety of ferrous waste and scrap such as cast iron and stainless steel. The global trade volume of ferrous scrap was 54.58 million tonnes in 1997 and increased to 146.7 million tonnes in 2008 before a sharp decline to 83.99 million tonnes in 2015 and a recovery to 103 million tonnes in 2018.

As shown in *Table 6.5.*, the major exporting countries for ferrous scrap trade are the United States of America, Japan, Germany, and Russia. These four countries accounted for 37.6% of total iron scrap exports in 2019. They achieved industrialisation early and steel products are widely used there. The end-of-life recycling of steel products provides waste ferrous scrap for reuse.

Turkey, the main scrap importing country in *Table 6.5.*, relies on electric arc furnaces to produce 26 million tonnes or 70% of the total crude steel production of about 38 million tonnes of mostly long products. As a result, ferrous scrap imports in 2019 were 18.9 million tonnes, or 19.1% of the total global scrap imports accounted in the database.

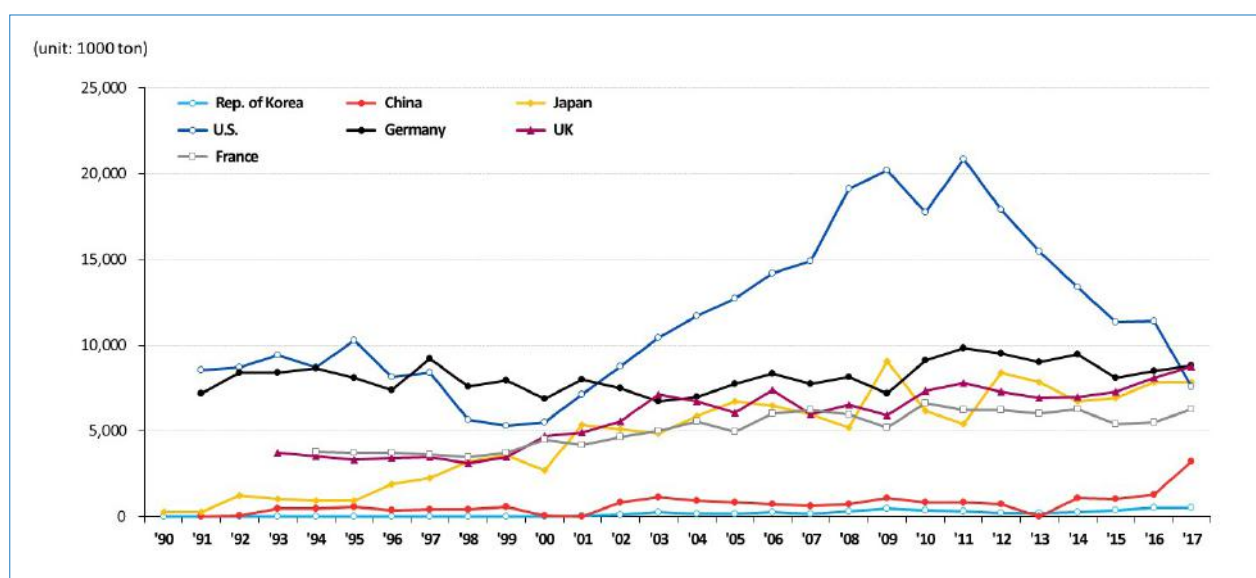
The second highest importer of scrap was Korea, which has a self-sufficiency rate of about 80%. The balance of scrap necessary for maintaining the steel production level in Korea is typically imported from Japan, but some scrap imports are obtained from the United States, Ukraine or Russia depending on logistics costs.

In the case of China, the proportion of imports plummeted to 0.2 million tonnes in 2019, following steady decrease in ferrous scrap exports due to increasing internal use over the past decade. The Vice Chairman of the China Iron Scrap Association suggested that ferrous scrap production in China in 2017 was 200 million tonnes, an increase of 67% compared to the previous year, and that domestic demand for cost-competitive ferrous scrap would continue to expand.

Description		Major countries/regions				World	Remark
		USA	Japan	Germany	Russia		
Export	Mass	17.7	7.7	7.9	3.7	98.5	Traditionally strong steel producing developed countries/regions with a high percentage of manufacturing industries tend to maintain a large supply of steel scrap
	%	18.0	7.8	8.0	3.8	100.0	
Description		Major countries/regions				World	Remark
		Turkey	China	Korea	Taiwan, China		
Import	Mass	18.9	0.2	6.5	3.5	98.7	Countries/regions with low self-sufficiency and high EAF production
	%	19.1	0.2	6.6	3.5	100.0	

**Table 6.5.** World ferrous scrap trade status for key export / import countries/regions (MT)  
Data: World Steel Association (2020)

Developed countries, such as the United States, the United Kingdom, Germany, Japan and France, dominate the global export market as shown in Fig. 6.22a..



**Fig. 6.22a.** Scrap export amounts by the major export countries, plus China and Korea

In the early 2000s, the United States led the ferrous scrap export market compared to other countries. In later years, US export volume was comparable to that of Germany and Japan. The high export quantities for particular countries indicate not only the availability of scrap in all forms but also the infrastructure and logistics present within these countries. High quality scrap for export applications is ensured through collection, sorting, hazardous material removal processing, shredding and additional sorting. Local public policies can also influence the scrap industry. In the case of China, the export tax of ferrous scrap has significantly increased, while the proportion of imports decreased. Although it is difficult to remove all unwanted elements, including tramp elements, from ferrous scrap, obsolete scrap can be partially refined to ensure steelmakers may utilise these commodities with reasonable additional costs. Large ferrous scrap suppliers typically have integrated facilities with shears, shredders, magnetic separators, and other heavy equipment to ensure ferrous scrap specifications are met.

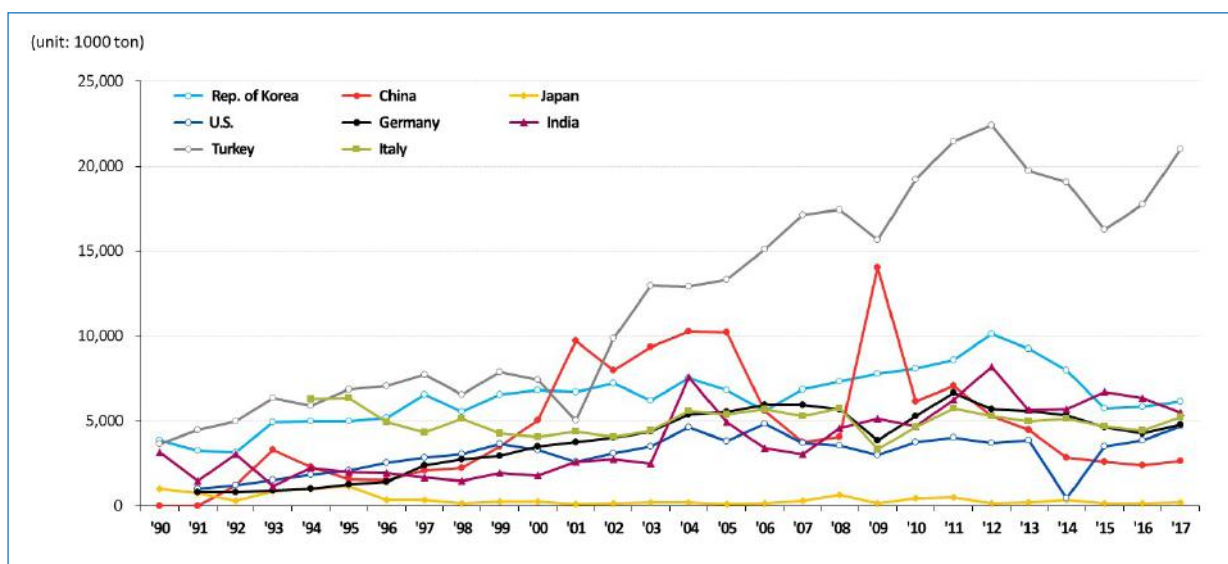


Fig. 6.22b. Scrap import amounts by the major import countries

Regarding import volumes, as shown in Fig. 6.22b., Turkey imports more than twice as much ferrous scrap as other countries.

The network analysis of the total ferrous scrap accumulated between 1990 and 2017, based on the export volume of ferrous scrap, is schematically shown in Fig. 6.23.. Korea mainly imports ferrous scrap from the United States and Japan. For Japan, there is no import quantity as Japan is self-sufficient in ferrous scrap. It is understood that many developed countries have a secure source of ferrous scrap for their own consumption.

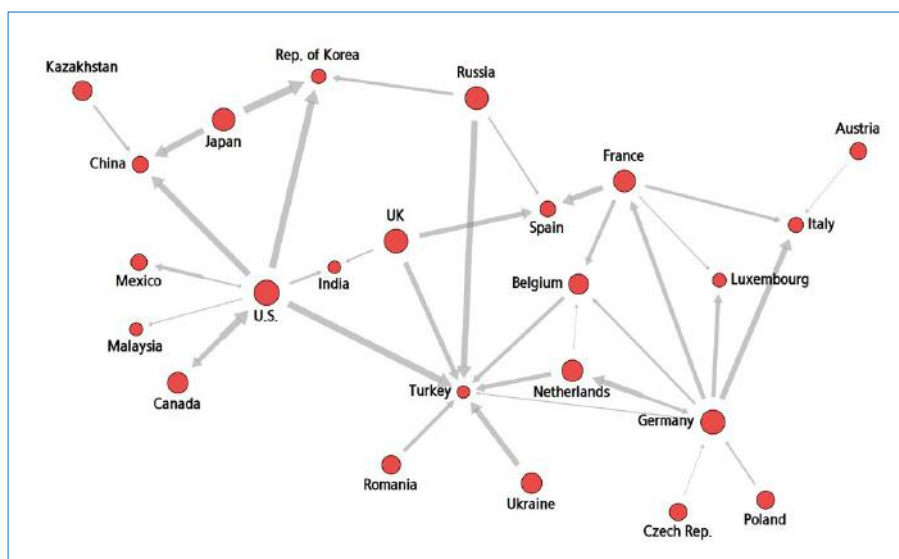


Fig. 6.23. Export network analysis of ferrous scrap from 1990 to 2017. Thicker lines correspond to larger export volumes. Figure provided by Il Sohn.

#### 4.2.2. Status of ferrous scrap recycling and utilisation technologies

Various types of ferrous scrap contain significant levels of recirculating tramp elements including copper (Cu) and tin (Sn). These tramp elements cannot be removed through the existing oxidative refining technologies in the primary and secondary refining processes of steelmaking. They can influence the hot-rolling response, surface quality, and end-product microstructure and properties. Current practices involve scrap dilution utilising scrap substitutes DRI or pig iron, and / or the pre-removal of the impurities by the physical separation and purification of the scrap before melting. Thus, improved technology to remove accumulated impurities from waste ferrous scrap with complex shapes and chemistries is necessary for effective recycling to occur.

#### 4.2.2.1. Scrap substitutes for the dilution of tramp elements

Ferrous scrap containing significant tramp element concentrations are typically diluted with pig iron or DRI in the absence of high-grade new scrap with little to no tramp elements. These scrap substitutes are high in iron (Fe) and have little to no tramp elements. Pig iron, also known as crude iron or carbon-saturated iron, also contains gangue materials of silicon dioxide ( $\text{SiO}_2$ ) and other oxides, and is typically obtained in the shape of ingots or nodules. Depending on the method of producing the pig iron, these iron sources may also contain significant amounts of sulphur and phosphorus, which may limit their use as sole substitutes for ferrous scrap. There are three main types of merchant pig iron, which include basic pig iron, foundry pig iron (hematite pig iron), and high purity pig iron (nodular pig iron). According to the International Iron Metallurgy Association (IIMA)<sup>42</sup>, pig iron comes in a variety of ingot sizes and weights ranging from 3 to more than 50 kg. Its typical composition is shown in *Table 6.6*.

Pig iron type	C	Si	Mn	S	P
<b>Basic grade</b>	3.5 - 4.5	≤1.25	≤1.0	≤0.05	0.08-0.15
<b>Foundry</b>	3.5 - 4.1	2.5 - 3.5	0.5 - 1.2	≤0.04	≤0.12
<b>High Purity/Nodular</b>	3.7 - 4.7	0.05 -1.5	≤0.05	≤0.025	≤0.035

*Table 6.6.* Typical pig iron chemical composition by the three major pig iron types according to the IIMA.

Due to the significant levels of sulphur and phosphorus within pig iron, steelmaking operations would require significant time and effort to refine such elements utilising existing primary and secondary refining operations. In particular, refining in the electric arc furnace process is severely limited considering the comparatively low flow, compared to the basic oxygen furnace (BOF), and low basicity of the refining slag. Thus, the complete substitution of ferrous scrap with pig iron would likely be impossible and, considering that pig iron production employs carbon sources, the availability of pig iron in the near future will likely be limited unless a carbon-neutral source, such as biomass, if available in sufficient quantities, is employed.

Besides pig iron, the other scrap substitute that is utilised is DRI or HBI (hot briquetted iron). DRI or HBI is typically produced by reducing iron ore in its pellet form with natural gas or carbon, although hydrogen may be increasingly used in the future. According to Midrex, the majority of DRI produced globally use natural gas as the reducing agent in vertical shaft-type furnaces, involving approximately 78 MT (75% of global DRI) of production. The rest is produced from composite pellets of coal and iron ore utilising horizontal rotary kilns or rotary hearth furnaces. Depending on the requirements of the customers, the carbon content can be controlled within a relatively broad range. Similar to pig iron, sulphur and phosphorus may need to be removed within the steelmaking operations.

Unlike pig iron, DRI and HBI are limited in size, and they experience greater difficulty in melting and recovery into liquid steel: further process developments are needed. Hot charging into the steelmaking process is encouraged where possible, but significant capital investment would be needed from the steel industry to accommodate this advantage. Clear advantages of DRI and HBI are the consistent quality and low residual content of the iron source, the low nitrogen (N) content and the possibility of continuously charging into the steelmaking operations. If the trend to lower the carbon footprint in steelmaking continues as anticipated, there should be a significant increase in demand for DRI and HBI. Furthermore, as hydrogen becomes more readily available at lower costs, natural gas could be replaced by hydrogen gas, which would lower the carbon footprint to the DRI manufacturing process. The complete substitution of natural gas with hydrogen might be unlikely considering carbon is needed for the DRI to produce steels. It should also be noted that DRI is pyrophoric; a minimum carbon content of approximately 2% by mass is thus desired to ensure safe handling and distribution without any need for special handling. Worldwide growth in DRI production since 1970 is summarised *Fig. 6.24*.

<sup>42</sup> <https://www.metallurgy.org/pig-iron.html>

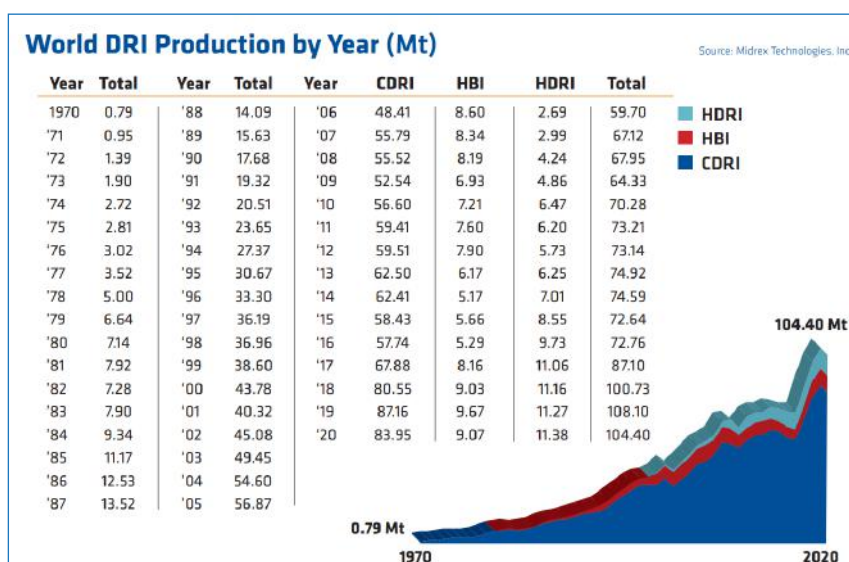


Fig. 6.24. World DRI annual production from 1970 to 2020 according to Midrex Technologies, Inc. (<https://www.midrex.com/wp-content/uploads/Midrex-STATSbookprint-2020.Final.pdf>)

#### 4.2.2.2. Physical and chemical methods to remove impurities

In order to remove impurities from iron scrap, physical and chemical removal methods are employed. Various methods for physically removing tramp elements such as copper (Cu), tin (Sn), etc. have been proposed by European automobile manufacturers, but practical use and economic analysis have yet to be reported. Steel-makers are naturally reluctant to incur costs associated with obtaining cleaner scrap. An improved business model that satisfies both the scrap supplier and user should be developed in the near future to improve the quality of obsolete scrap.

For scrap containing non-ferrous metals, a low-temperature crushing method can be used. It is indeed possible to separate only one component by crushing the ferrous scrap below the withdrawal temperature, proceeding to the extraction at different temperatures. However, the cost of the refrigerant is typically high and the energy to maintain the temperature works against the purpose of developing a greener steel manufacturing process because the economics may be unsustainable.

In other research projects, impurities have been removed using molten aluminium (or magnesium), building on the low Cu activity in molten aluminium-based alloys in the range of 600 °C -750 °C. However, these methods require additional process design, and capital investments and technology at an industrial scale has yet to be fully realised.

#### 4.2.3. Implications and Future Prospects

Ferrous scrap is a clean source of iron for reducing carbon dioxide and is efficiently used as a social asset rather than waste. Technology development for the removal of chemical impurities from ferrous scrap is in progress.

The use of ferrous scrap is expected to gradually increase along with growing emphasis on greenhouse gas regulations. Integrated steel mills typically use on average about 15% of ferrous scrap together with molten hot metal; increasing the use of ferrous scrap can reduce the amount of greenhouse gas generated per tonne of molten steel. In line with the strengthening of environmental regulations, it is expected that the development of power-saving technologies will be required, such as VOC control technology, electric furnace sealing technology, and preheating methods, along with technology for removing impurities from iron-based scrap.

If greater utilisation of ferrous scrap is achieved in the oxygen steelmaking converter, some additional process considerations will apply. Additional energy will be needed to provide the necessary steel temperatures by increasing the amount of dissolved silicon in the converter for subsequent silicon oxidation (heating). Silicon is elevated in the integrated steel mill by reducing the extent of desiliconisation during hot metal pre-treatment. However, when the amount of silicon increases, so does the amount of silicon dioxide (SiO<sub>2</sub>) generated in the converter and additional limestone input is required to control the slag composition, thereby increasing the

total amount of slag generated and reducing the effective volume for molten steel production. Therefore, if the amount of ferrous scrap is increased, it may become necessary to modify the operation philosophy from maximum productivity to efficient productivity in the converter consistent with new operational constraints.

Furthermore, it should be noticed that steel products generally have a service life of between 30 and 40 years and the available scrap base today would therefore correspond to global production 30 to 40 years ago, which was then less than half of present production. The available scrap base will therefore continuously increase but for the foreseeable future always considerably lag behind needs until the day when eventually steel production stabilises.

## 5. Challenges related to the decarbonisation of the manufacturing processes

As mentioned in *Section 2.*, there are at present two main manufacturing methodologies for steelmaking. These are via the Integrated Blast Furnace / BOF processing route, which converts virgin raw materials into liquid steel, or via the electric arc, which melts steel scrap alongside a range of other ferrous bearing materials, such as Direct Reduced Iron (DRI), sponge iron, or pig iron. Both methodologies have strengths and weaknesses built into the investment model for the manufacturing site, with investment cycles for new technologies and processes lasting throughout the lifespan of the site, which can often be measured in decades.

### 5.1. Investment needs, stranded assets and return of capital

The future availability of cheap energy from low-carbon sources and low-carbon electricity and associated regulation regarding carbon taxation will be the two key drivers for the adoption of hydrogen-based steel via either BF / BOF or HDRI. Although the goal of becoming carbon neutral is still 20 to 30 years ahead, several European companies have already declared their intention to transition sooner rather than later.

Industrial sites have lifetimes that can exceed 50 years and investment planning horizons of 10 to 15 years. Asset and footprint decisions should follow a clear decarbonisation road map that combines long-term goals with actionable quick wins to allow for a gradual shift toward decarbonisation that keeps all stakeholders on board. Globally, the route to decreasing emissions is likely to be a transitional one, regional interests and technological availability being the limiting factors that impede the rate of progress.

Globally, BF / BOF steelmakers are already optimising BF / BOF processes with ladle furnaces, Torpedo Lidding and scrap-preheating. In the future, it is likely that as furnaces head towards end of life they will begin switching to the EAF using scrap and DRI powered with natural gas or imported HBI. The ultimate pathway is likely to end up with carbon-neutral EAF production using a mix of scrap and hydrogen-based DRI. The precise mix of scrap versus DRI-based production using EAFs will depend on future product portfolios. The development and commercialisation of DRI method using hydrogen will be key to enabling the production of high purity steel grades in the future with low carbon dioxide emissions. Another challenge facing global steelmaking will be OEM availability and an appropriately skilled workforce to install and operate the low carbon steel value chain.

In December 2021, Bloomberg NEF (BNEF) released “Decarbonizing Steel: a net Zero pathway<sup>43</sup>”. In this report, BNEF highlighted that global steel production could be achieved with nearly zero carbon emissions via an investment of USD 278 billion. Critical to this transition was investment in both hydrogen generation and scrap recycling. The report broke down future steelmaking methodologies into the following groups: a) green hydrogen: 31% of the market; b) recycling: 45% of the market; c) carbon capture, utilisation / storage (CCUS) retrofitted assets or molten ore methodologies: the remainder.

The availability of low-cost hydrogen and electricity will likely drive the direction in which each different country progresses alongside other investments around CCUS within the country. At present, there are several companies around the world that have already announced their intentions for at least initial CO<sub>2</sub> reduction.

### 5.2. Access to and cost of low-carbon hydrogen and regulations

Hydrogen today faces two major challenges within the steel industry to be regarded as a ‘low carbon’ fuel source. At the present time, indeed, hydrogen generation is mainly driven by steam methane reforming (SMR), also known as ‘gray hydrogen’. SMR forms both hydrogen and carbon dioxide. This process can be enhanced

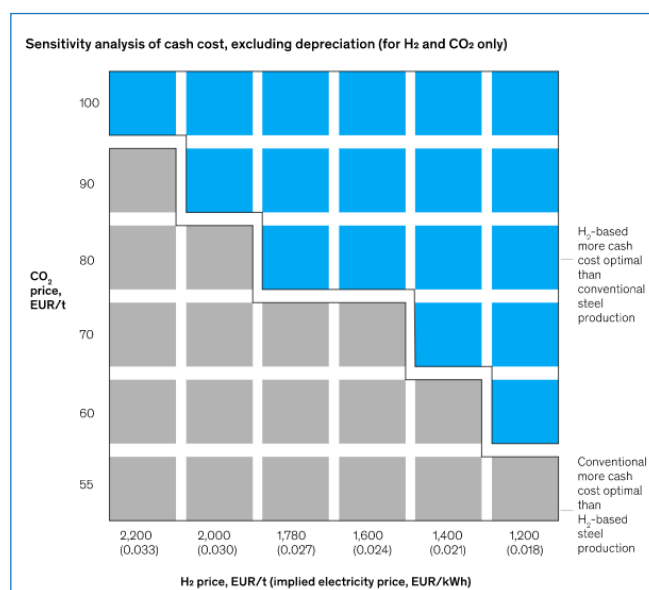
<sup>43</sup> <https://www.recyclingtoday.com/article/steel-decarbonization-scrap-hydrogen-roles/>

via CCS, with the produced hydrogen consequently earning the term ‘blue hydrogen’. Additionally, hydrogen can be manufactured with no carbon dioxide emission via the electrolysis of water – this is termed ‘green hydrogen’.

Hydrogen has been proven within several routes of introduction to the steel manufacturing process. These methodologies increase the cost of the steel manufacturing process and require significant investment to retrofit existing infrastructure to handle hydrogen either as an injectant in the blast furnace as a replacement for Pulverized Coal Injection (PCI), as proven by Thyssenkrupp, or as a source for sponge iron or DRI manufacturing. As proven by both HYBRIT (SSAB & Vattenfall) and the Midrex process.

Today, the cost/price of low-carbon hydrogen is very high compared to either gray (from methane) or blue (produced with gas and CCS). The price, however, is expected to decrease over the coming decades (See *Chapter 0. To set the scene, Annex 2.*). To put this into perspective, the total electricity needed to produce two million tonnes of hydrogen-based steel is about 8.8 TWh. With the current cost of CO<sub>2</sub> emission taxes increasing towards EUR 100/tCO<sub>2</sub>, and the cost of hydrogen production reducing as manufacturing methodologies mature, hydrogen-based steel production could soon become more cost-optimal than conventional steel production, as shown in *Fig. 6.25.* This indicates at what cost low-carbon electricity needs to fall to ensure the cost-effective production of hydrogen.

Depreciation is ignored in the figure as steelmaking assets are largely written off over their investment cycle. It must be highlighted that the capital expenditure (CAPEX) required for hydrogen-based steelmaking will be very significant, with electric arc mills, DRI plants alongside the hydrogen electrolyzers, transport, storage networks all being required.



**Fig. 6.25.** Hydrogen Price vs. CO<sub>2</sub> price<sup>44</sup>.

Exhibit from “Decarbonization challenge for steel”, June 2020, McKinsey & Company, [www.mckinsey.com](https://www.mckinsey.com). Copyright (c) 2022 McKinsey & Company. All rights reserved. Reprinted by permission.

Another concern that needs to be reviewed and will affect the economics is raw material availability. To switch production from BF / BOF to DRI / EAF using hydrogen, raw material changes are necessary and will especially increase demand for DR pellets. The security of DR supply in the case of a massive switch to hydrogen-based steel production is uncertain and could result in rising price premiums, negatively affecting the economics of the new production method. Moreover, to guarantee carbon neutrality throughout the whole value chain, close cooperation with steel suppliers, such as the iron ore industry, is essential. For example, mining companies need to evaluate the business case to invest in upgrading their iron ore to DR-grade pellets or even produce HDRI.

<sup>44</sup> <https://www.mckinsey.com/~media/McKinsey/Industries/Metals%20and%20Mining/Our%20Insights/Decarbonization%20challenge%20for%20steel/Decarbonization-challenge-for-steel.pdf>

### 5.3. Political and economic regulations and incentives as driving forces to implement low-carbon technologies

There are a number of potential pathways to decarbonisation. There is no worldwide agreement regarding the methodology for handling assets at different ranges of ages. Within Europe, carbon cost has been consistently increasing over the past several years, so much so that alternative technologies around carbon sequestration or utilisation are starting to be economically viable. The Emissions Trading Scheme (ETS) for carbon price breached EUR 100/t in the UK on 4 February 2022, while the EU ETS carbon price was very close to that level. Such an increase in ETS carbon prices will make fossil-based manufacturing less and less economically viable. Taking into account the related induced changes in the cost of natural gas- and coal-based power generation for energy-intensive industries, this should lead to an intensification of discussions around energy generation methodologies by national administrations.

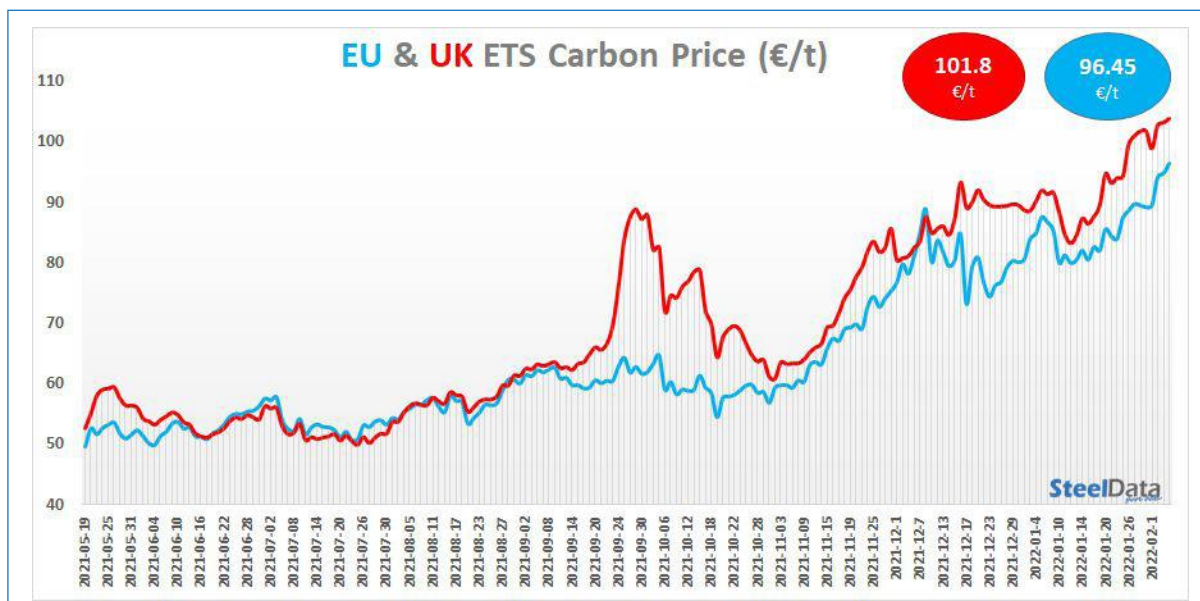


Fig. 6.26. EU & UK ETS Carbon Price (€/t CO<sub>2</sub>)

Under many modelled scenarios, there are needs for a significant economic transformation over the coming decades for a net-zero emission industry to be achieved by 2050. One of the interesting issues that may impact global decarbonization is how in a foundation industry such as iron and steel, circular economy will cope with increasing energy needs due to the long-term diminution of the grade of iron ore (its percentage in iron oxide). Furthermore, in the case of iron and steel, it may affect the availability of Direct Reduced Iron type products.

The future availability of cheap energy from low-carbon sources and associated regulation regarding carbon taxation will be the two key drivers for the adoption of hydrogen-based steel via either BF / BOF or HDRI. These drivers will be critical in order to ensure that using hydrogen technology has a better cost/benefit ratio than using traditional technologies, as shown in the matrix of Fig. 6.25. in Section 5.2. above.

### 5.4. Availability and reliability of low-carbon electricity

Electrification is a key option in the decarbonisation of the steel industry. It entails a real increase in demand of low-carbon electricity: a) in general, as a solution to replace the use of fossil fuels in heating and heat treatment and in the electrification of operations, machinery and internal transport systems in mining and steel manufacture; b) but above all in the production of hydrogen for DRI processes in electrolyzers and the increase of electric arc furnaces (EAFs).

This will induce an increasing low-carbon generation capacity in the electricity power systems. Depending on regional and local conditions, political positions and measures and incentives, this demand for increasing electricity generation demand will mostly be covered by hydropower, onshore and offshore wind power, and solar or nuclear power. If accepted, using small modular reactors could be an option in some cases.

Generation capacity together with cost efficiency and security of supply will be a challenge for future success. This requires large investments in transmission and distribution networks.

As an example of the increased need for low-carbon electricity, the Swedish mining and mineral group LKAB announced that its transition towards a sustainable future would proceed at a faster pace and with higher targets. When the transition is completed, with increased production, by around 2050, the target for LKAB is to produce 24.4 million tonnes of sponge iron per year, with zero carbon dioxide emissions. LKAB's demand, which mainly aims at producing hydrogen gas, is estimated at 20 TWh per year by 2030, increasing to 50 TWh by 2040 and finally reaching 70 TWh per year when the entire expansion is realised by 2050.

### 5.5. Trade barriers

On a global basis, trade barriers may be different in each country due to the differentiated electricity and hydrogen supply potential for each region. Ultimately, this may result in the economic differentiation of hydrogen supply and the ensuing electricity mix for each country.

### 5.6. Permission processes and political instruments

New or rebuilt process facilities involving new technologies, the use of hydrogen and increased electricity demand, etc. require approval from political decision makers and authorities. There is a need for clear, appropriate and effective permit granting processes for investments, encompassing both the national and global aspects and taking into account the benefits brought about by the products of the industry.

In particular, infrastructure changes for increased electricity transmission and hydrogen production and storage needs improved and shortened lead times to enable the necessary investments to take place.

Public policies (regulations, incentives) should be transparent and stable to help all stakeholders to act. This implies a shift in views on the trade policy functions that strive to set global rules, harmonise taxes, for example carbon taxes and environmental policy instruments, and avoid distortion measures. Societal issues should be taken into consideration.

### 5.7. Bridging the skills gap

As in many other sectors, one of the critical issues beyond production technology or material availability is skills shortage. The transformation of the global steel industry over the next 15 to 20 years will require a workforce of highly skilled engineers and scientists to install and calibrate the volume of equipment required.

Transitions to greener economies will have a significant impact on certain sectors of a country's economy, demand for new types of skills and the changing nature of occupations.

Skills shortages are acting as a barrier to driving transitions to greener economies forward. Scaling up the use of green technologies, for example, requires people with the right set of skills to adapt to them. Furthermore, the success of implementing green policies is dependent on the availability of skilled people. People losing jobs in the transition to a low-carbon economy need to develop new skills that are valuable for upcoming opportunities – and it is critical to know the type and quality of skills required. Finally, skills-led strategies to support the green transition may serve as drivers of change in their own right: the availability of a suitably skilled workforce attracts investors to green industries, while the environmental awareness that is encouraged through education and training boosts demand for green products and services.

Identifying and anticipating skills needed for the green and low-carbon economy is thus a prerequisite to training decisions, for acquired skills to be relevant for the labour market. It has been highlighted by many different think tanks that industry and policymakers need to work together to minimise the disruption caused by the decarbonisation shift and installation of additional electrical and industrial infrastructure.

Three key pathways worth reflecting upon:

**1. Identifying and bridging skills gaps**

Harness the existing expertise of the engineering construction workforce and repurpose skills to tackle the net-zero challenge.

**2. Minimising skills shortages**

Engineering and Construction companies should embrace a range of new technologies and business models such as collaboration, system thinking and digitalisation to ensure the workforce is sufficiently prepared to deliver the decarbonisation agenda. Engineering careers should be made more appealing with a drive toward highlighting how critical this industry is to tackle climate change. This also includes increasing the availability of apprenticeships to be trained in high voltage fitting and other skilled careers.

**3. Leveraging policy and innovation**

Education and Industry should work closely together at a regional level to enable policy and educators to reflect regional skill requirements. This is critical to support a range of potential methodologies to meet net-zero emissions, such as industrial clusters observed in the United Kingdom, which will require a pipeline of skilled workers to be trained over the coming decades.

The European Union has published a Research Brief which may support any company or policymaker looking towards anticipating future requirements<sup>45</sup>.

## 6. Case Studies

The previously mentioned Midrex process and HyREX and HYBRIT case studies described further below demonstrate low CO<sub>2</sub> emission.

During the implementation of the report, the Working Group held web seminars with presentations given by representatives of interesting projects and future technologies. The seminars allotted time for questions and discussion. Their results are described in the case studies below.

In addition to these detailed presentations, the Group, during its work, noted other ongoing activities of interest. Data has been studied from available public information and reports. Some of it has been collected and is mentioned in the report as interesting examples that would be advantageously studied and followed up in the future.

As a result of the format of available information, each of the 6 case studies below is structured in its own way. In the case of China, in particular, two separate examples are presented.

### 6.1. China: Decarbonisation Plan and hydrogen metallurgy

China is the largest steelmaking nation in the world with 1 064.8 million tonnes produced in year 2020. It accounts for around 55% of the total world production. In the framework of its 14<sup>th</sup> Five-Year Plan, the government of China is promoting more stringent controls on energy consumption and energy intensity. Furthermore, China is implementing a plan to achieve the carbon emission peak by 2030 and carbon neutrality by 2060. Therefore, reducing the carbon emissions of China's iron and steel industry has become an important issue.

#### 6.1.1. Action Plan for carbon emission decrease in China

China is committed to reaching its carbon peak in 2030 and carbon neutralisation in 2060. In 2021, the State Council of the People's Republic of China (PRC) issued its "Opinions on the complete, accurate and comprehensive implementation of the new development concept and the carbon neutralization work" and "Action Plan for Carbon Dioxide Peaking before 2030"<sup>46</sup>, thus defining timetable, roadmap and construction drawings. According to the latter, the policies for the steel industry are to be the following.

<sup>45</sup> [https://www.ilo.org/wcmsp5/groups/public/---ed\\_emp/---ifp\\_skills/documents/publication/wcms\\_168352.pdf](https://www.ilo.org/wcmsp5/groups/public/---ed_emp/---ifp_skills/documents/publication/wcms_168352.pdf)

<sup>46</sup> Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy)-National Development and Reform Commission (NDRC), People's Republic of China  
[https://en.ndrc.gov.cn/policies/202110/t20211024\\_1300725.html](https://en.ndrc.gov.cn/policies/202110/t20211024_1300725.html)  
<https://news.metal.com/newscontent/101678929/%22china-baowu-carbon-neutralization-action-plan%22-released-to-explore-new-ideas-of-green-low-carbon-metal-lurgy-in-the-industry>

- To improve the reform of the supply-side structure for the steel industry, which means to rigorously execute production capacity replacement and promote the optimisation of the existing capacity while controlling the expansion of the production capacity and phasing out any outdated production capacity.
- To promote mergers and the reorganisation of steel enterprises across regions and ownership types, in order to increase the concentration of the industry.
- To spur structural optimisation in the steel industry and substitutions with clean energy by means of vigorously promoting demonstrations of non-blast furnace technology, improving the recycling and reuse of steel scrap and advancing the use of electric furnaces that can be totally charged with steel scrap.
- To promote the application of advanced and appropriate technologies, which means researching the available potential for energy saving and carbon reduction, encouraging steel production to combine with the chemical industry, developing demonstrations on hydrogen metallurgy and CCUS, and promoting heating development with low-grade residual heat.

#### 6.1.2. China Baowu Steel Group Corporation Ltd.

*China Baowu* is the biggest steel maker in China with a production of crude steel around 115 million tonnes in 2021. In 2016, *China Baowu* launched a project for technological innovation in green and low-carbon metallurgy. Research is focused on: low-carbon blast furnace ironmaking technology based on the hydrogen-rich carbon cycle, hydrogen metallurgy processes (hydrogen-based shaft furnace direct reduction); CO<sub>2</sub> capture and utilisation technology of off-gas, etc. Recently, the company has established a Low-Carbon Metallurgy Innovation Centre and initiated 10 scientific research projects, including on hydrogen metallurgy technology and hydrogen enrichment carbon cycle blast furnace technology.

In October 2019, *China Baowu* began to reactivate the Bayi Iron and Steel Low-Carbon Metallurgy Technology Innovation Base to test their new low-carbon blast furnace ironmaking technology based on hydrogen enrichment carbon cycle oxygen blast furnace, to which CO<sub>2</sub> capture and utilisation have also been applied. In 2020, the hydrogen-rich carbon cycle blast furnace fulfilled the goal of 35% oxygen in blast gas, breaking through the oxygen enrichment limit of the traditional blast furnace, and completing the test task of the first stage. The innovation of the hydrogen enrichment carbon cycle in the ultra-high oxygen blast furnace was then realised for the first time, carbon consumption was reduced by 15%, and the test task of the second stage was completed. The transformational re-engineering is expected to be completed by the middle of 2022, after which the industrial test of hydrogen enrichment carbon cycle in total oxygen blast furnace will be carried out.

*China Baowu* plans to start the construction of a hydrogen-based shaft furnace DRI demonstration project producing 1 million tonnes per year at the Zhanjiang Low-Carbon Metallurgical Technology Innovation Base. Natural gas, coke oven gas and hydrogen will be applied simultaneously, and 60% of the reduction gas will be hydrogen. The construction is expected to start in early 2022 and be put into operation in 2023. In phase II of this project, the construction of another set of hydrogen-based shaft furnaces each producing 1 million tonnes steel per year and equipped with electric arc furnace steelmaking is planned. It is also planned to use green hydrogen – i.e. hydrogen produced through low-carbon energy electrolysis – and the proportion of hydrogen will gradually reach up to 80% ~ 90%.

#### 6.1.3. HBIS Group CO., Ltd

HBIS Group is the second-largest steelmaker in China with an output of 45 million tonnes of crude steel in 2021. In March 2019, HBIS, together with the strategic consulting centre of the Chinese Academy of Engineering, China Iron & Steel Research Institute Group (CISRI) and Northeastern University, established a Hydrogen Energy Technology and Industrial Innovation Centre, to facilitate cooperation in the planning of hydrogen energy development, applied technology and industrial distribution and other issues.

In November 2019, HBIS signed a memorandum of understanding (MOU) with the Italian Tenova Group for close cooperation in hydrogen metallurgy technology. Cooperation is planned with Sinosteel and other institutions in a demonstration project of 1.2 million tonnes of hydrogen metallurgy using the most advanced hydrogen production and reduction technology in the world.

In November 2020, HBIS signed a contract with Tenova for a project of high-tech hydrogen energy development and utilisation, including an ENERGIRON direct reduction plant with an annual output of 600 000 tonnes.

In March 2021, HBIS and BHP Billiton Ltd. signed a MOU to cooperate in three key areas: hydrogen DRI technology, steel slag treatment and recycling technology, and improvement in the efficiency of iron ore utilisation.

In May 2021, Xuanhua Iron and Steel Co., Ltd. a HBIS subsidiary officially launched the hydrogen metallurgy demonstration project at a scale of 1.2 million tonnes. The project adopts ENERGIRON-ZR (zero reforming) technology, which can replace the traditional blast furnace carbon metallurgy process. The annual carbon emission reduction is expected to reach 60%<sup>47, 48</sup>.

## 6.2. Japan: COURSE 50

According to the report written by the Japan Iron and Steel Federation<sup>49</sup>, the Japanese steel industry is poised to achieve carbon neutrality by 2050 by using domestic CO<sub>2</sub> reduction processing technologies and products. These notably include the drastic reduction of CO<sub>2</sub> in blast furnaces through the COURSE 50 project (CO<sub>2</sub> Ultimate Reduction System for Cool Earth 50) and ferrocoke technologies with CCUS, as well as the development of hydrogen-based ironmaking. In addition, the expanded use of scrap and biomass are also interim bridge technologies to achieve the policies of the Japanese government.

COURSE 50, supported by the New Energy and Industrial Technology Development Organization (NEDO), is now in Phase 2 (2018-2025). Phase 1 started in 2008 and the industrial application of the developed technology is expected to start in 2030 with widespread technology transfer by 2050.

Compared with future hydrogen-based ironmaking technologies, COURSE 50 attempts to optimise existing facilities at integrated steel works, taking in consideration the high levels of efficiency already achieved by the existing facilities that are similar to the steel works and are found in Korea. Within the COURSE 50 project, hydrogen-containing coke oven gas is used to boost the hydrogen-induced reduction. Furthermore, reducing the energy required for the separation of CO<sub>2</sub> from blast furnace off-gases, and recovering waste heat from the steelworks are two projects under development. According to a review of the various low-carbon emissions projects by Zhang et al.<sup>50</sup>, the COURSE 50 objective is to reduce carbon emissions by 10% using hydrogen and by another 20% through the separation and recovery of CO<sub>2</sub> from the blast furnace gas. Thus, the target for the project is a total reduction of 30%. Approximately 10 test trials have been carried out for the COURSE 50 test blast furnace installed at Nippon Steel's East Nippon Works Kimitsu Area<sup>51</sup>.

## 6.3. Republic of Korea: POSCO<sup>52</sup>

In December 2020, the Republic of Korea committed to carbon neutrality by 2050 and expressed its firm intention to reduce CO<sub>2</sub> emissions by 40% below its 2018 levels by 2030, which it then confirmed in the Nationally Determined Contribution by 2030 (NDC) signed at COP26. This increases pressure on the Korean steel industry, which accounts for 14% of total CO<sub>2</sub> emission in Korea, to transform the main steelmaking route – so far based on the conventional BF-BOF – to lower carbon emission steel manufacturing processes. Aligning with the Korea's NDC commitment, POSCO declared that the company would reach carbon neutrality by 2050 and set up a roadmap taking into consideration raw materials, energy supplying conditions, and available technologies.

POSCO plans to pursue the challenging and proactive pathway towards carbon-neutrality while keeping its current crude steel production at the current level of 38 Mt/yr. Compared to the average figures between 2017 and 2018, CO<sub>2</sub> emissions will be 10% lower by 2030. This target will be achieved by optimising manufacturing processes with smart technologies and intelligent manufacturing.

In parallel and in order to maximise the efficiency of the existing facilities, low carbon blast furnace (BF) iron-making technologies will be developed. Such technologies are based on the increased usage of high iron-bearing raw materials and H<sub>2</sub>-rich gas in BF. Electric arc furnaces (EAF) for scrap melting are also planned to be

<sup>47</sup> [https://www.sohu.com/a/503976517\\_120174089](https://www.sohu.com/a/503976517_120174089)

<sup>48</sup> [http://www.gov.cn/zhengce/content/2021-10/26/content\\_5644984.htm](http://www.gov.cn/zhengce/content/2021-10/26/content_5644984.htm)

<https://news.metal.com/newscontent/101678929/%22china-baowu-carbon-neutralization-action-plan%22-released-to-explore-new-ideas-of-green-low-carbon-metallurgy-in-the-industry>

<sup>49</sup> [https://www.course50.com/en/news-en/2021/n0215\\_01\\_en/](https://www.course50.com/en/news-en/2021/n0215_01_en/)

<sup>50</sup> X. Zhang, K. Jiao, J. Zhang and Z. Guo, Journal of Cleaner Production, 2021, Vol. 306, 127259

<sup>51</sup> [https://www.course50.com/en/news-en/2020/n1223\\_01\\_en/](https://www.course50.com/en/news-en/2020/n1223_01_en/)

<sup>52</sup> <https://www.centricbusinesssolutions.com/energy-solutions/financing/industrial-energy-transformation-fund-ietf>

<https://www.spglobal.com/platts/en/market-insights/latest-news/metals/092221-uk-expands-ietf-funding-to-steelmakers-to-launch-clean-steel-fund>

<https://www.ft.com/content/dcb1f109-8d79-4c68-bc69-c26f7a2b2c4e>

installed in the integrated steelworks. An innovative steelmaking technology that maximises the use of scrap during steelmaking processes is also being developed: the top and bottom oxygen blowing converter. These technologies will contribute up to 50% of the reduction of CO<sub>2</sub> emissions by 2040.

Carbon capture, utilisation, and storage (CCUS) will be a part of the low carbon solution in POSCO. The economic evaluation is ongoing because the economic feasibility of large-quantity CO<sub>2</sub> separation remains yet unclear, and several pilot scale projects are being discussed to confirm commercial viability.

POSCO plans to build the Hydrogen Reduction (HyREX) pilot plant for low-carbon ironmaking based on fluidised bed reduction technology by 2028 (See Fig. 6.27.). It is notable that fine iron ore or sinter feed is directly used for the fluidised bed reaction, in contrast to the high-quality pellets required in the shaft-type hydrogen reduction technology, as in SSAB's HYBRIT plant.

In POSCO's HyREX, the fine iron ore or sinter grade is reduced by hydrogen in the multi-staged fluidised bed reactors. The HyREX fluidised bed reactor is designed to use fine iron ore with a wide range of size distribution. Four fluidised bed reactors are sequentially installed at the different levels and connected by a standpipe to enable the material flow between the reactors. The temperature and retention time in each reactor are optimised to attain a high reduction degree. After being reduced by green hydrogen, the direct reduced iron is subsequently melted and further refined in the melting furnace powered by electricity. Considering the use of the fine iron ore or sinter grade, the melting furnace is designed to accommodate the direct reduced iron with high gangue content.

POSCO's choice of fluidised bed reactor is made on the basis of iron ore supply conditions. The abundance of sinter-feed iron ore will be an alternative solution because of the expected shortage of high-grade pellets.

HyREX is expected to be more competitive as it directly uses fine ore, which is abundant. The easier supply of heat between reactors to compensate for the heat deficiency caused by the strong endothermic reaction of hydrogen reduction is an advantage of HyREX multi-stage fluidised bed reactors.

POSCO has been operating the largest fluidised bed reactors in the world to produce 2.5 Mt/yr DRI in FINEX plants. The fluidised bed technologies of FINEX plants will apply to HyREX pilot plant of 1.0 Mt/yr capacity, where the hydrogen fluidised bed reducing reactors are directly connected to the melting electric furnace. The pilot plant will be built by 2028, and commercialisation feasibility will be verified by 2030.

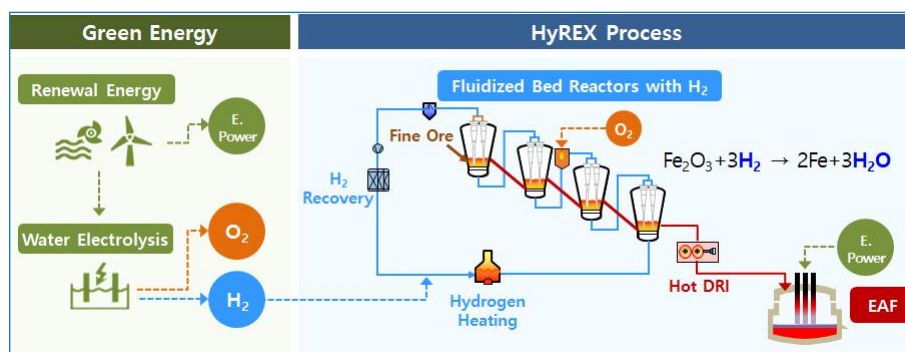


Fig. 6.27. The HyREX Process using 'green' energy  
Source: POSCO

Cooperation with raw material companies on the issues of low-carbon raw materials to reach carbon neutrality in steel manufacturing is in progress. Business models regarding green hydrogen production and transport and raw material selection for hydrogen steelmaking are also being discussed<sup>53</sup>.

<sup>53</sup> Video Clips introducing HyREX: <https://www.youtube.com/watch?v=9u3l2lfuDnc>  
HyIS 201 Forum Homepage: <https://h2ironsteelforum.com>  
Newspaper Articles: <http://www.koreaherald.com/view.php?ud=20211006000840>  
<https://newsroom.posco.com/en/various-aspects-of-the-worlds-first-international-hydrogen-iron-steel-making-forum-hyis-2021/>

## 6.4. Sweden: HYBRIT (Hydrogen Breakthrough Ironmaking Technology)<sup>54</sup>

### 6.4.1. Introduction

The main actors in Swedish iron and the steel industry are the mining company LKAB and the steel manufacture SSAB.

LKAB AB, a government owned Swedish company, is an international mining and minerals group that offers sustainable iron ore, minerals and special products. LKAB is one of the oldest industrial companies of Sweden, established in 1890. It is wholly owned by the Swedish state. LKAB produced 26.7 million tonnes iron ore products in 2021.

SSAB is a highly specialised global steel company, starting back in 1878, listed on the Swedish stock exchange, Nasdaq Stockholm. The production plants of SSAB in Sweden, Finland and the United States of America have an annual steel production capacity of approximately 8.8 million tonnes.

Most steel in Sweden is produced via traditional blast furnace technology with coal and coke used as energy sources and for reduction. The steel industry is one of the highest carbon dioxide emitting industries, accounting for up to 10% of Swedish CO<sub>2</sub> emissions.

The strategy to decarbonise the steelmaking process focuses on the direct reduction of iron ore by green hydrogen (produced by low-carbon electrolysis). Sweden offers favourable conditions such as a high-quality niche production of iron-ore pellets, a specialised and innovative steel industry, and an abundant supply of low-carbon electricity.

In 2016, Hybrit Development AB, which is owned by SSAB, LKAB and the state-owned energy company Vattenfall, started developing technology to make steel using hydrogen gas instead of coal. The initiative has the potential to reduce Sweden's overall carbon dioxide emissions by 10% and 7% in Finland, as well as contribute to cutting steel industry emissions in Europe and globally.

### 6.4.2. Technology

Low-carbon steel production, using the Hydrogen Breakthrough Ironmaking Technology (HYBRIT), will eliminate the formation of CO<sub>2</sub> by using low-carbon reductants and energy sources. In the case of *HYBRIT*, sponge iron is produced by using hydrogen gas as the reductant. The production route is similar to existing direct reduction processes, except for the carbon dioxide emissions: hydrogen reacts with iron oxides to form water instead of carbon dioxide. Hydrogen gas (H<sub>2</sub>) is produced by the electrolysis of water using low-carbon electricity, which is already the standard in Sweden.

*HYBRIT* pilot projects cover the whole value chain. Their main characteristics are:

- low-carbon mining operations through electrification and automation
- low-carbon electricity supply
- low-carbon heating by bio-oil or hydrogen to replace coal & oil in the sintering of iron ore pellets
- hydrogen production via electrolysis using low-carbon electricity, mainly hydro and wind power
- hydrogen storage as a major part of the future electrical grid, involving more wind / solar power
- shaft furnaces for iron ore reduction
- tailor-made pellets as iron ore feed
- preheating of the hydrogen reduction gas mixture using electricity before injection into the shaft
- products can be either low-carbon DRI or HBI (Hot Briquetted Iron)
- DRI / HBI is melted together with recycled scrap in electric arc furnaces using limited amounts of bio-carbon during melting.

The principal flow diagram of the HYBRIT technology compares its production process to the current blast furnace production process, including differences in energy use and carbon emissions.

<sup>54</sup> Hybrit ([hybritdevelopment.se/en/](https://www.hybritdevelopment.se/en/))  
 SSAB is taking the lead in decarbonizing the steel industry: <https://www.ssab.com/en/fossil-free-steel>  
 SSAB, LKAB: <https://www.lkab.com/en/>

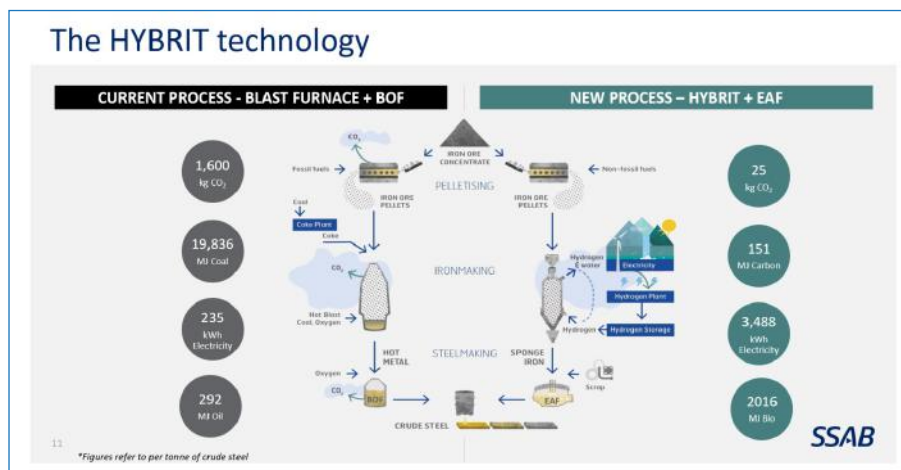


Fig. 6.28. HYBRIT flow diagram

Original in Swedish: <https://www.hybritdevelopment.se/en-fossilfri-framtid/en-vardekedja-for-fossilfritt-stal/>

In English: <https://www.usinenouvelle.com/article/comment-la-suede-remonte-la-chaine-de-l-acier-zero-carbone.N1034939>

#### 6.4.3. Timeline for low-carbon steel production

A pilot direct reduction plant, the first of its kind, was launched in 2020 with a capacity of 1 tonne per hour. In July 2021, SSAB Oxelösund rolled the first steel produced using the HYBRIT technology and delivered it to a customer, Volvo Group, which then manufactured the world's first vehicle made out of low-carbon produced steel: a load carrier for use in mining or quarries.

During the year 2020, the world's first low-carbon iron ore pellets were produced at a pilot plant at the LKAB site in Malmberget, using bio-oil.

An adjoining pilot plant for underground hydrogen storage has been built and was inaugurated on 14 June 2022. It will be a pressurised lined rock cavern (LRC) with a volume of 100 m<sup>3</sup>. The test programme will last two years.

The next phase will then be the construction of an industrial demonstration plant, a necessary step in the development prior to full commercial operation. This demonstration plant will produce hydrogen and manufacture sponge iron by direct reduction with hydrogen. The facility is planned in Gällivare, LKAB's iron mine site. The plan is to commission the facility in 2026. The project will produce approximately 1.35 Mt HDRI per year. The sponge iron will be used by SSAB's planned electric arc furnace meltshop in its steel plant in Oxelösund, also planned for commissioning in 2026. This demonstration step will lead to the phasing out and shutdown of SSAB's current coke oven-blast furnace-BOF meltshop facilities and cut Sweden's total CO<sub>2</sub> emission by approximately 3%. The HYBRIT initiative is granted support from the European Union, as one of seven large-scale innovative projects under the Innovation Fund.

SSAB has made the policy decision to fundamentally transform Nordic strip production and accelerate the company's green transition. The decision was taken against the background of strongly growing demand for low-carbon steel. The plan is to replace the existing system with the new HYBRIT technology to produce HDRI, and to invest in two electric arc furnace-based minimills with continuous casting/continuous rolling, eliminating in principle all fossil fuel use for high quality strip production. The ambition is to avoid further blast furnace relinings before BF is permanently phased out when the new mills are in operation, and to largely eliminate carbon dioxide emissions around 2030 – in other words 15 years earlier than previously announced. However, to achieve this ambition, the necessary infrastructure, with access to low-carbon electricity, should be all set in time.

#### 6.5. United States of America

The majority of raw steel production in the United States employs scrap-based recycling in the electric arc furnace, either exclusively (Nucor, Steel Dynamics, TimkenSteel, Commercial Metals, Evraz, SSAB) or to a growing extent (US Steel). EAF production exceeds 70% in both the United States and North America, so that the

decarbonisation of primary steel production requires access to low-carbon electricity from the grid or via installations collocated with the steel production facility. Such installations are being implemented with wind and solar power uptake agreements with local utilities (Nucor is an example of it) and on-site capacity such as the Bighorn solar farm at EVRAZ<sup>55</sup> in Pueblo, Colorado (in conjunction with Lightsource BP).

EVRAZ is a leading North American producer of engineered steel products for rail, energy and industrial end markets. It has signed a partnership and long-term agreement with Xcel Energy and Lightsource bp to build a 300 MW solar facility in Pueblo, Colorado, where EVRAZ has one of its production sites. The facility, called Bighorn Solar, will provide low-carbon electricity to the new EVRAZ long rail mill, now under construction, and existing EVRAZ Rocky Mountain Steel facilities in Pueblo. This is an example of efforts in North America to employ low-carbon power to convert recycled scrap metal into new, clean steel.

Bighorn Solar entered commercial operation in December 2021. Lightsource bp developed, financed, and will continue to own and operate the 300-megawatt utility-scale solar project.

The USA also has abundant natural gas resources, with methane-based DRI installations that are also hydrogen-capable for the future<sup>56</sup>.

Producers are establishing aggressive goals for carbon neutrality and monitoring developments in hydrogen steelmaking, carbon capture, etc. At the same time, the US government is investing substantially in research and deployment of decarbonisation technologies. A number of US steel producers are also linked to overseas multinational companies, and so are participating in hydrogen and other decarbonisation demonstration projects in other parts of the world (e.g. ArcelorMittal, SSAB, and voestalpine).

## 6.6. Further Cases

The availability of low-cost hydrogen and electricity will likely drive the direction in which each different country progresses alongside other investment around CCU / S within the country. At present, there are several companies around the world that have already announced their intentions for at least initial carbon reduction.

### 6.6.1. ArcelorMittal, France, Germany, and Spain

In France, ArcelorMittal has announced its decarbonisation strategy with two electric arc furnace sites and a Direct Reduced Iron (DRI) plant, using hydrogen instead of coal, to be installed in Dunkirk and Fos-sur-Mer at a cost of USD 1.95 billion. The new industrial facilities will be operational starting in 2027<sup>57</sup>.

At the ArcelorMittal steel plant in Hamburg, the “Hamburg H2 Project” is designed to test the ability to replace the use of natural gas with hydrogen to reduce iron ore and form DRI on an industrial scale, as well as to test then how such low-carbon DRI reacts in an EAF. The facility is scheduled to start in 2025, producing around 100 000 tonnes per year<sup>58</sup>.

ArcelorMittal Spain signed a memorandum of understanding (MoU) with the Spanish Government in July 2021. This MoU will see an investment of EUR 1 billion in the construction of a green hydrogen direct reduced iron (DRI) plant at its plant in Gijón, as well as a new hybrid electric arc furnace (EAF). ArcelorMittal will have access to green hydrogen supplied through a consortium of companies that will cooperate in the construction of the infrastructure required to both produce hydrogen in the Iberian Peninsula using solarpowered electrolysis and transport it directly through a network of pipelines.

The new DRI unit and EAF are expected to be in production before the end of 2025. The Gijón DRI plant will also feed the company’s Sestao plant, where production is already entirely from the electric arc furnace route. This means that by 2025 ArcelorMittal Sestao will produce 1.6 million tonnes of steel with zero carbon emissions<sup>59</sup>.

<sup>55</sup> EVRAZ North America (evrazna.com) and Bighorn Solar Project in the USA | Lightsource bp

<sup>56</sup> See for example: <https://www.clevelandcliffs.com/sustainability/steel-as-a-sustainable-material/producing-clean-steel>

<sup>57</sup> ArcelorMittal France: <https://www.recyclingtoday.com/article/arcelormittal-steel-recycling-dri-france-investment/>

<sup>58</sup> ArcelorMittal Hamburg: Hamburg H2: [Working towards the production of zero-carbon emissions steel with hydrogen | ArcelorMittal and Hydrogen-based steelmaking to begin in Hamburg | ArcelorMittal.](https://corporate.arcelormittal.com/media/press-releases/arcelormittal-signs-mou-with-the-spanish-government-supporting-1-billion-investment-in-decarbonisation-tech-nologies)

<sup>59</sup> ArcelorMittal Spain: <https://corporate.arcelormittal.com/media/press-releases/arcelormittal-signs-mou-with-the-spanish-government-supporting-1-billion-investment-in-decarbonisation-tech-nologies> and <https://corporate.arcelormittal.com/media/press-releases/arcelormittal-sestao-to-become-the-world-s-first-full-scale-zero-carbon-emissions-steel-plant>

### 6.6.2. TATA Steel NL

In the Netherlands, TATA Steel NL announced its intention to transition its assets towards EAF and hydrogen-based DRI manufacturing. This transition includes significant investment from national and foundation industries within the Netherlands<sup>60</sup>.

This provides evidence that, although many of these sites have potentially stranded assets, the growing desire of customers for so-called green steel makes it more and more viable in commercial and financial terms to begin this transition with significant CAPEX investment.

While neither British Steel, nor TATA Steel UK have announced their decarbonisation strategy yet, the UK government has decided significant investment strategies across the Humber and South Wales region to supply heavy industry with hydrogen and for CCU/S transport solutions<sup>61</sup>. In parallel, R&D and initial technology up-scaling are being funded via such national research bodies as the Engineering and Physical Sciences Research Council (EPSRC) and Innovate UK via the challenge funds and "Clean Steel" grants of the Industrial Energy Transformation Fund (IETF)<sup>62</sup>.

### 6.6.3. H2 Green Steel, Sweden<sup>63</sup>

H2 Green Steel (H2GS AB), a new Swedish company, was founded in 2020 with the ambition to accelerate the decarbonisation of the steel industry, using green hydrogen.

H2GS is launching a fully integrated greenfield steel plant in Boden, in the north of Sweden. The plant will be using low-carbon electricity to electrolyse hydrogen and thus conduct a DRI process, which will reduce emissions by more than 95%. Fossil-free electricity will then be used in the electric arc furnaces. The aim is to bring emissions down to zero.

H2 Green Steel has almost the same goal and aim as the HYBRIT project, which has inspired it.

Depending on permit permissions, construction work is scheduled to start in 2022 and the facility is expected to start production in 2024 at the earliest with a capacity of up to 2.5 million tonnes hot- and cold-rolled steel. The capacity will then ramp up between 2026 and 2030 to reach a yearly production of 5 million tonnes low-carbon steel. The investment is expected to be in the order of EUR 2.5 billion.

H2GS has signed customer contracts in different industries for more than 5 to 7 years and over 1.5 million tonnes per year. Customers that have signed term sheets or supply agreements for steel so far include BMW Group, Electrolux, Mercedes-Benz, Miele, and Scania.

### 6.6.4. Thyssenkrupp Steel, Germany<sup>64</sup>

Thyssenkrupp Steel at Duisburg, Germany, has launched a project, H2Stahl, to expand the use of hydrogen to their blast furnace No. 9, including the construction and trial operation of a direct reduction pilot plant using green hydrogen. The project is supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK) and will mark the technological leap to hydrogen-based climate-neutral hot metal production.

<sup>60</sup> TATA Steel Netherlands: <https://eurometal.net/tata-steel-picks-hydrogen-dri-eaf-path-for-ijmuiden/>

<sup>61</sup> UK government investment strategies across Humber and South Wales regions to supply heavy industry with hydrogen and CCU/S transport solutions: <https://www.swic.cymru/> and <https://www.zerocarbonhumber.co.uk/>

<sup>62</sup> <https://www.centricbusinesssolutions.com/energy-solutions/financing/industrial-energy-transformation-fund-ietf>  
<https://www.spglobal.com/platts/en/market-insights/latest-news/metals/092221-uk-expands-ietf-funding-to-steelmakers-to-launch-clean-steel-fund>  
<https://www.ft.com/content/dcb1f109-8d79-4c68-bc69-c26f7a2b2c4e>

<sup>63</sup> <https://www.h2greensteel.com/>

<sup>64</sup> [Climate-neutral future of steel production: Real-world laboratory of the energy transition H2Stahl project to start at Duisburg site of thyssenkrupp Steel](#) and [Hydrogen: an energy carrier for the future \(thyssenkrupp.com\)](#)

## 7. Key messages and recommendations

### Key Messages

1. The steel industry plays a prominent role in today's world, in terms of production volumes and sales (1950 Mt in 2021). The steel industry is at the same time a major source of CO<sub>2</sub> emissions: in 2020, its total direct emissions were of the order of 2.6 Gt<sup>65</sup>, representing between 7% and 9% of global anthropogenic CO<sub>2</sub> emissions.
2. In the transition towards global decarbonisation, steel remains a necessary material in a wide range of applications. The use of steel is expected to continue to increase in the future, even with recycling and the more widespread use of scrap metal as a raw material. In addition, market demand for low-carbon steel is already rising and highly valued.
3. In the existing production processes, coal is the dominant energy source, accounting for about 16% of global coal demand in 2019. On the whole, the BF / BOF route is mainly used, representing 73.2% of the production processes worldwide vs. 26.3% for the EAF, although there are substantial differences across regions and countries.
4. The increased use of EAF and the use of scrap will contribute to decreasing carbon emissions. Technologies that contribute to improving the quality of final products from scrap may be further developed.
5. Although there is no single final scenario, the direct reduction of iron ore (DRI) using low-carbon hydrogen is now regarded as the most viable option and the long-term solution to achieving carbon-neutral steel production. Various processes are under development and at pilot scale: their economic viability will certainly be proven before 2030. The availability and cost of low-carbon hydrogen will be key for the massive implementation of these processes.
6. Existing technologies with an appropriate Technology Readiness Level (TRL) already contribute to decreasing CO<sub>2</sub> emissions. Such technologies are related to energy efficiency, the use of biofuels, utilisation of residual energies, electrification, and direct reduction of iron ore by gas instead of coal.
7. CCS in combination with steel production has not yet been proven on an industrial scale. This could change during the course of this decade with several projects at different stages of implementation in different countries.
8. Huge investments are needed to replace or renew facilities may imply stranded assets.

### Recommendations

The recommendations in *Chapter 0*. concerning public policies, regulations, capital intensive sectors, education and skills are without any doubt valid for the iron and steel sector.

#### 7.1. On increasing scrap use

We recommend expanding the use of steel scrap, which may be regarded as an important green resource for reducing greenhouse gas emissions, through not only the adoption of common rules and specifications but also the development and implementation of new scrap processing technologies to improve the removal of impurities.

#### 7.2. On modifications that allow existing facilities to reduce CO<sub>2</sub> emissions

Considering the urgency of reducing CO<sub>2</sub> emissions and the lifetime of many existing facilities, we recommend implementing every possible and economically affordable, even marginal, reduction of CO<sub>2</sub> emissions for existing steel plants: partial electrification in heating, the use of biomass, utilisation of residual energies, better command-control, etc.

#### 7.3. On a potential acceleration of the timing of CO<sub>2</sub> emissions reduction

We recommend that the existing important projects and demonstration plants that will lead to scalable breakthroughs at industrial and commercial levels be sufficiently incentivised and promoted so as to rapidly deploy in the 2030s or even earlier if possible.

#### 7.4. On Research and Development

<sup>65</sup> <https://www.iea.org/reports/iron-and-steel>

Funding for long term research – typically 10 years or more – and knowledge development needs to be secured and creative and unique solutions should be supported. We therefore recommend that support for pilot and test facilities be maintained or even increased, and more resources be made available for basic and applied research and up-scaling, as well as to enforce collaborative research involving the industry on a global scale.

#### **7.5. On Education and Training**

We recommend taking advantage of the gradual changes ahead and the associated development of new knowledge and skills needed to design, build and operate this new world of iron and steel. This would attract more young people to this sector, which is considered less attractive than others in many countries. As practical knowledge is likely to originate at the engineering level, we recommend promoting the ‘spill-over’ effects from such knowledge to universities and other institutions.

#### **7.6. On Permitting**

New or rebuilt process facilities, new technologies, the use of hydrogen and increased demand for electricity, etc. – these all require political approval from the authorities. In order to foster the necessary investments and accelerate their realisation, we recommend that the permitting processes be clear, appropriate, stable and efficient, i.e. simplified and accelerated in many countries.

#### **7.7. On global cooperation and partnerships**

The steel industry is a globally competitive and capital-intensive industry. We recommend supporting cooperation and partnerships in the development of new technologies and sharing experience and costs in order to accelerate development, make technology licensing available at a fair price and, at the same time, ensure competition.

## 8. List of abbreviations and acronyms

---

<b>BF</b>	Blast Furnace
<b>BOF</b>	Basic Oxygen Furnace
<b>CDRI</b>	Cold Direct Reduced Iron
<b>CCS</b>	Carbon Capture and Storage
<b>CCUS</b>	Carbon Capture, Utilisation and Storage
<b>COVID-19</b>	Coronavirus Virus Disease 2019.
<b>DME</b>	Dimethyl Ether
<b>DRI</b>	Direct Reduced Iron
<b>EAf</b>	Electric Arc Furnace
<b>EU ETS</b>	European Union Emissions Trading System
<b>EUROFER</b>	European Steel Association, based in Brussels, Belgium
<b>EW</b>	Electrowinning, a hydrometallurgical process for metal recovery
<b>GHG</b>	Greenhouse Gas
<b>H-DR</b>	Hydrogen Direct Reduction
<b>HDRI</b>	Hydrogen Direct Reduction Iron
<b>HBI</b>	Hot Briquetted Iron
<b>HQ scrap</b>	Pre-consumer scrap
<b>HYBRIT</b>	Hydrogen Breakthrough Ironmaking Technology by LKAB & SSAB (Sweden)
<b>HyREX</b>	A pilot plant for Hydrogen-based Reduction to be built by POSCO (Republic of Korea)
<b>IEA</b>	The International Energy Agency, based in Paris, France
<b>IETF</b>	Industrial Energy Transformation Fund (Netherlands)
<b>IIMA</b>	International Iron Metallurgical Association
<b>LPG</b>	Liquefied Petroleum Gas
<b>LQ scrap</b>	Post-consumer scrap
<b>MIIT</b>	The Ministry of Industry and Information Technology of China
<b>M&amp;E</b>	Monitoring and Evaluation
<b>NDC</b>	Nationally Determined Contribution (COP 26 Paris Agreement)
<b>NEDO</b>	New Energy and Industrial Technology Development Organization (Japan)
<b>OEM</b>	Original Equipment Manufacturer
<b>OHF</b>	Open Hearth Furnace
<b>OPEX</b>	Operational Expenditure
<b>PRC</b>	People's Republic of China
<b>SAF</b>	Submerged Arc Furnace
<b>SMR</b>	Steam Methane Reforming
<b>tce</b>	tonnes of coal equivalent
<b>Tecnocored</b>	An ironmaking process using biomass as a reductant
<b>TGRBF</b>	Top Gas Recycling Blast Furnace
<b>toe</b>	tonnes of oil equivalent
<b>VOC</b>	Volatile Organic Compounds
<b>WSA</b>	World Steel Association

---

## CHAPTER 7. INFORMATION TECHNOLOGY AND DATA CENTRES

### **Members of the Working Group**

**Duggan Gerry**, Ireland

**Gao Kulun**, China

**Gelenbe Erol**, United Kingdom (Co-chair)

**O'Brien Kieran**, Ireland

**Sansò Brunilde**, Canada (Co-chair)

**Wang Yishen**, China

## Table of Contents

---

<b>Executive Summary</b> .....	265
<b>1. Introduction</b> .....	266
1.1. The challenge of measuring ICT's electricity consumption and CO <sub>2</sub> impact .....	267
1.2. Is there evidence that high ICT Penetration results in Reduced CO <sub>2</sub> Impact? .....	268
1.3. Worldwide estimate of electricity consumption by ICT and its CO <sub>2</sub> impact .....	269
1.4. The effects of evolving technologies .....	270
<b>2. Data centres: the special perspective provided by the Irish experience</b> .....	271
2.1. Background .....	271
2.2. Data centres .....	272
2.3. Generation issues .....	273
2.4. Recent developments .....	273
<b>3. Key message and recommendations</b> .....	274
3.1. Data centre energy consumption .....	274
3.2. Energy consumption of 5G technology and beyond .....	275
3.3. Edge computing .....	275
3.4. ICT energy and CO <sub>2</sub> statistics .....	275
3.5. Optimal replacement of ICT Equipment to Improve its Environmental Impact .....	275
<b>Abbreviations, definitions and acronyms</b> .....	276

## Executive Summary

---

In today's world, it would be difficult to find even one human activity bare of any support from Information and Communications Technology (ICT). From financial services to theatre ticket bookings, from takeaway food to medical scans, all activities are increasingly becoming dependent on the availability of efficient and effective ICT.

Energy is consumed by the ICT industry in a number of ways:

1. in the manufacturing of digital hardware, such as integrated circuit chips, digital circuit boards, computers, optical equipment and fibres, which represents 50% of ICT's electricity consumption;
2. in the extraction and processing of such necessary minerals as silicon and rare earths, for example;
3. in the entirely electricity-driven operation of computing and network hardware (laptops, data centres, network routers, optical and digital transmission switches, wireless transmission systems, etc.);
4. in the decommissioning and recycling of defective or obsolete ICT equipment.

In many cases, on the other hand, ICT can dramatically reduce energy consumption. Video conferences as substitutes for air travel are a prime example but there are many more. This brief chapter discusses Bullet Points 1 and 3 and attempts to determine the key quantitative questions related to these issues from available data.

This chapter does not address the important aspects discussed in Bullet Points 2 and 4, e.g., the extraction of materials that are key to ICT equipment manufacturing, nor does it highlight the concerns that ICT decommissioning raises.

The chapter identifies public policy dilemmas, as policymakers simultaneously promote both the expansion of ICT facilities and reduction in GHG emissions. Its recommendations may be summarised as follows.

- Continue improving data centre efficiency through improved facility management, timely load shifting and continuous improvement in Power Usage Effectiveness (PUE).
- Recognise the significant energy consumption associated with 5G networks. Encourage network sharing and improve base station energy management.
- Carry out further research on the energy performance of edge computing systems versus cloud servers. Develop appropriate metrics in order to be able to improve analysis.
- Recognise the inadequacy of publicly available energy data in the ICT sector and set public standards for the measurement, storage and publication of ICT energy consumption and GHG emissions data.
- Introduce judicious policies for the replacement of ICT equipment, due to the high energy consumption for manufacturing of ICT which represents 50% of the total, and the high environmental impact of ICT decommissioning.

## 1. Introduction

The global energy consumption of Information and Communications Technology (ICT) and its consequent impact on greenhouse gas emissions (GHGs) remains a controversial topic, on which experts and organisations often express divergent views<sup>1,2</sup>. Two factors significantly contribute to such a divergence of views:

- The lack of a precise definition of what an ICT system is. Does it include or not home entertainment or financial technology (Fintech) for example?
- The lack of systematic measurement data.

Fig. 7.1. below is a simplified description of the broad boundaries of ICT systems. It primarily describes the type of hardware deployed.

End-users, on the other hand, typically account for their sole devices (hardware) and numerous applications (software). Yet ICT energy consumption depends on the hardware of the overall system<sup>3</sup> and the – often underestimated – energy used to manufacture that very same hardware.

As a rule of thumb, ICT manufacturing consumes as much electricity as ICT operations. It also results in the consumption of electricity and other forms of energy for the extraction of minerals and production of materials needed to manufacture ICT components and systems.

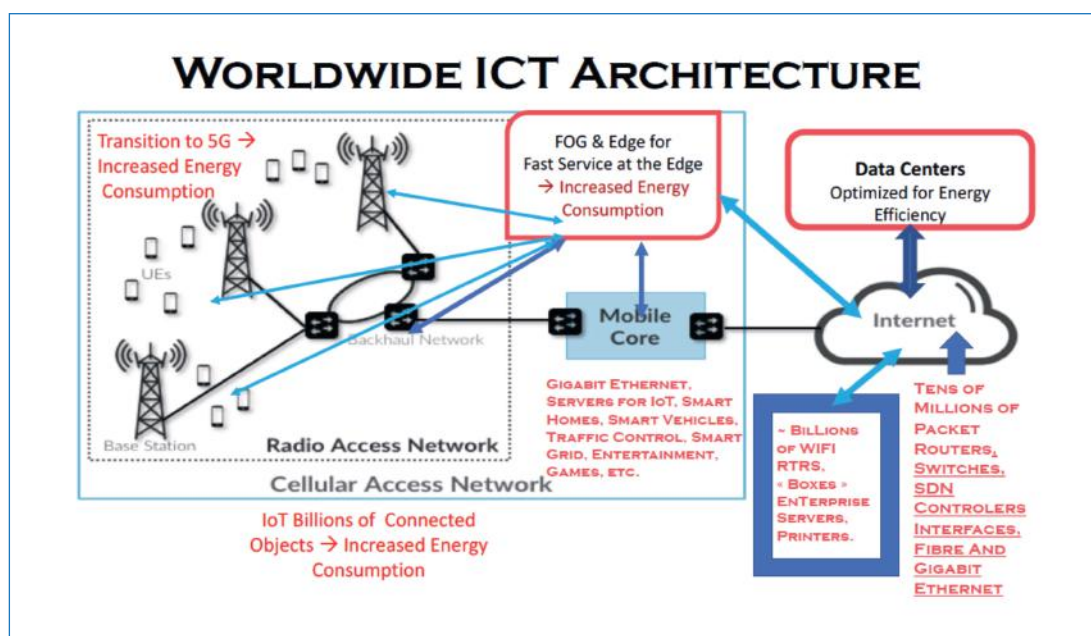


Fig. 7.1. Worldwide ICT architecture (Copyright Erol Gelenbe)

<sup>1</sup> H. Ferreboeuf et al. Lean ICT: Towards Digital Sobriety. The Shift Project, March 2019, [https://theshiftproject.org/wp-content/uploads/2019/03/lean-ict-report\\_the-shift-project\\_2019.pdf](https://theshiftproject.org/wp-content/uploads/2019/03/lean-ict-report_the-shift-project_2019.pdf)

<sup>2</sup> G. Kamiya. Data Centers and Data Transmission Networks. International Energy Agency, Paris, June 2020, <https://www.iea.org/reports/data-centers-and-data-transmission-networks>

<sup>3</sup> Giorgos Fagas, John P. Gallagher, Luca Gammaitoni and Douglas J. Paul, "Energy Challenges for ICT", Submitted: March 31st, 2016 Reviewed: November 2nd, 2016 Published: March 22nd, 2017, DOI10.5772/66678

On the left of *Fig. 7.1.* is displayed the Radio Access Network (RAN); it has transitioned through various generations (1G, 2G, 3G, 4G, LTE), now towards 5G, and the next step will be 6G. We will comment on the transition to 5G later.

The RAN uses wireless signals to offer connections to common mobile devices of all kinds. Such connections now extend to the Internet of Things (IoT), road traffic monitoring, various “smart” applications and important industrial ones (Industry 4.0)

The RAN connects via the mobile network operators and the “Backhaul” network, to the Mobile Core Network. Connections can be via wire, optical fibre and wireless (both terrestrial and space based). The Mobile Core Network is mainly a fibre and wire network with numerous routers and switches connecting to data centres and other “Cloud” services that support the wireless mobile network.

The RAN increasingly uses a technique referred to as Fog computing or Fog networking: an architecture that uses edge devices to carry out substantial amounts of computation, storage, and communication both locally and routed over the internet backbone. Such devices, placed in close physical proximity to the wireless base stations of the RAN, offer low latency access to data and other end users for highly interactive and data-intensive applications such as games, entertainment, or the IoT.

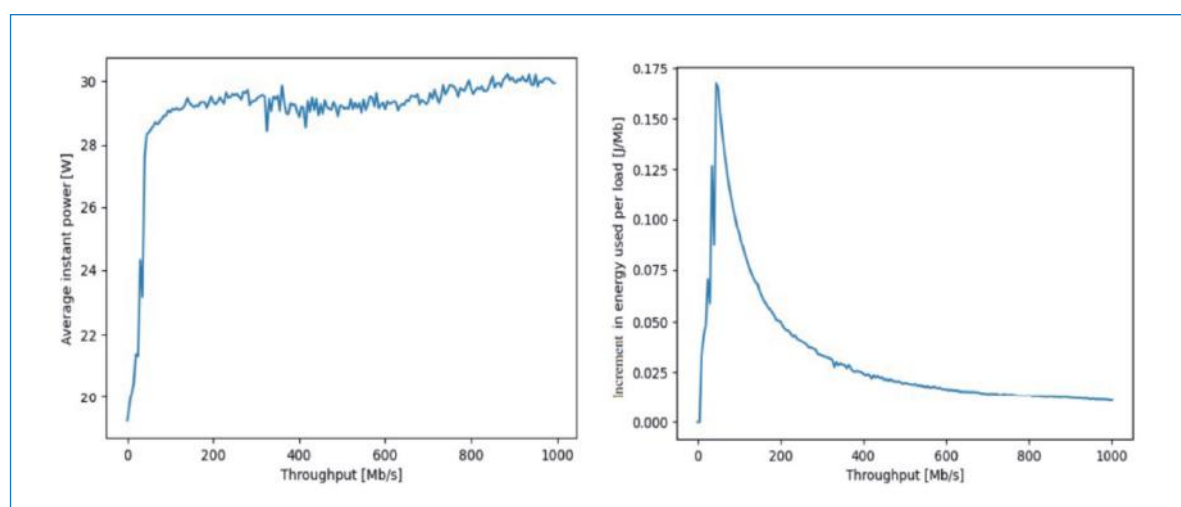
The Mobile Core also connects to the internet at large (at the right-hand side of the figure), which is composed of routers, switches and mainly fibre connectivity, including Gigabit Ethernet.

The internet itself connects to thousands of powerful data centres, millions of businesses and billions of homes. Connections today are typically made with high-speed internet wiring or fibre. Wi-Fi routers that facilitate end-user connectivity are ubiquitous and, additionally, provide access to mobile devices and IoT applications. Everything, from car charging stations to bicycle hiring and banking systems, is now serviced by the internet.

### 1.1. The challenge of measuring ICT’s electricity consumption and CO<sub>2</sub> impact

Although from a technical point of view it may be possible to detail what electricity ICT globally consumes, from a practical point of view it is not, given the many billions of devices in use and the huge datasets that would result, not to mention the additional electricity needed to store and process such datasets. This global picture would also fail to answer the fundamental question about ICT energy consumption: such consumption should ultimately include the energy used to manufacture, transport and deliver ICT devices.

Large ICT operators, such as data centres and communication network operators, do monitor and report on their energy consumption; yet this is not possible for all of the billions of devices that are used and connected to networks.



**Fig. 7.2.** Power consumption (Left) and Energy consumption Per throughput (Right). Characteristics of an Intel Network Unit of Computing (NUC), i.e. a small network connected PC, when used as a network router at the edge<sup>4</sup>.

<sup>4</sup> P. Fröhlich, E. Gelenbe, J. Fiolka, J. Checinski, M Nowak, and Z. Filus, “Smart SDN Management of Fog Services to Optimize QoS and Energy”, *Sensors* Vol. 21 (<https://doi.org/10.3390/s21093105>), p. 3105, MDPI, 2021

Given the complexity and the large amount of information exchange<sup>5</sup>, securing ICT networks has led to significant increases in energy consumption, however difficult it may be to measure them. There is a noticeable increase in electricity consumption during what is known as ‘cyber-attacks’.

Roughly estimating that 10% of ICT equipment capacity is devoted to cyber security and that 20% of ICT system operations are similarly employed, one can estimate that the annual global energy consumption of cyber security is 300 TWh. Using the recent International Energy Agency (IEA) estimate of 485 g of CO<sub>2</sub> per kWh, the total of global CO<sub>2</sub> emissions thus amounts to approximately 150 million tonnes of CO<sub>2</sub>.

However, considering that most operations used for online banking and payments are related to authentication and security processes, the amount of electricity actually used for securing our ICT systems is likely to be significantly higher.

## 1.2. Is there evidence that high ICT Penetration results in Reduced CO<sub>2</sub> Impact?

The computer industry tends to vaunt the increasing efficiency of digital equipment while those concerned with sustainability stress the projected increase of energy consumption by ICT as well as the expanding use of rare and polluting materials for the manufacture of digital devices and chips.

ICT is often put forward as the means to obtain savings in energy consumption – with resulting reduction in GHG emissions. Unfortunately, there is little if any evidence to this effect, and available data indicate that the countries with the highest levels of GHG emissions worldwide are also those with the highest shares of ICT penetration in their economies (see *Table 7.1.*)<sup>6</sup>. The ‘Bech Index’ is a measure of the volume of business-to-business economic activity in ICT per country. It is clear that some countries, having moved away from manufacturing to a more service-based economy, have seen their consumption of primary energy and electricity remaining stable or slightly decreasing. At the same time, the ‘imported CO<sub>2</sub> impact’ of these countries, due to their imports of manufactured goods, has increased.

While internet-based ‘homework’ and ‘home education’ have reduced the need for transport, home-based activities, on the other hand, may have increased home energy consumption from home heating or cooling. A careful analysis of the energy consumption and CO<sub>2</sub> impact data from the Covid-19 period will surely be enlightening in this respect. However, as a whole, and on a country-by-country and worldwide aggregate basis, there is no hard evidence to date suggesting that the increased penetration of ICT has actually reduced overall energy or electricity consumption and CO<sub>2</sub> impact and further research on the different trade-offs and balances surrounding this matter is needed.

<sup>5</sup> O. H. Abdelrahman and E. Gelenbe, “Signalling storms in 3G mobile networks”, 2014 IEEE International Conference on Communications (ICC), 2014, pp. 1017-1022, doi: 10.1109/ICC.2014.6883453.

<sup>6</sup> Hans Peter Bech, “And the Winners Remain CHINA and INDIA”, May 2020, doi: 10.13140/RG.2.2.10093.41440, <https://www.researchgate.net/publication/341599907>

## Top ICT Economies (Bech Index) and Top CO<sub>2</sub> Polluters

2017	2018	2019	2020	2021	Share 2021	Country
2	1	1	1	1	19.22%	China
1	2	2	2	2	16.36%	USA
3	3	3	3	3	8.02%	India
4	4	4	4	4	4.05%	Japan
5	5	5	5	5	3.16%	Germany
6	6	6	6	6	2.96%	Russia
7	7	7	7	7	2.48%	Brazil
10	10	10	9	8	2.43%	Indonesia
8	8	8	8	9	2.38%	UK
9	9	9	10	10	2.28%	France
12	11	11	11	11	1.77%	Mexico
11	12	12	12	12	1.74%	Italy
14	14	14	13	13	1.61%	South Korea
13	13	13	14	14	1.60%	Turkey
15	15	15	15	15	1.38%	Spain
16	16	16	16	16	1.36%	Canada
17	17	17	17	17	1.25%	Saudi Arabia
19	19	18	18	18	0.99%	Australia
18	18	19	19	19	0.94%	Iran
23	22	22	20	20	0.93%	Egypt
20	20	20	21	21	0.93%	Taiwan
21	21	21	22	22	0.89%	Thailand
22	23	23	23	23	0.86%	Poland
24	24	25	24	24	0.76%	Nigeria
25	25	N/A	25	25	0.75%	Pakistan

Rank	Country	Total CO <sub>2</sub> (kt)
1	China	10,313,460
2	United States	4,981,300
3	India	2,434,520
4	Euro area	2,207,420
5	Japan	1,106,150
6	Germany	709,540
7	S. Korea	630,870
8	Iran	629,290
9	Indonesia	583,110
10	Canada	574,400
11	Saudi Arabia	514,600
12	Mexico	472,140
13	South Africa	433,250
14	Brazil	427,710
15	Turkey	412,970
16	Australia	386,620
17	United Kingdom	358,800
18	Italy	324,850
19	Poland	312,740
20	France	309,960

Table 7.1. Top ICT Economies and top CO<sub>2</sub> polluters

(For the table to the left: [https://www.researchgate.net/publication/341599907\\_And\\_the\\_Winners\\_Remain\\_CHINA\\_and\\_INDIA/figures](https://www.researchgate.net/publication/341599907_And_the_Winners_Remain_CHINA_and_INDIA/figures)) and top CO<sub>2</sub> polluters. For the table to the right: <https://www.economicshelp.org/blog/10296/economics/top-co2-polluters-highest-per-capita/>) Tejvan Pettinger, 19 August 2021. Source of data: World Bank CO<sub>2</sub> emissions (kt)

### 1.3. Worldwide estimate of electricity consumption by ICT and its CO<sub>2</sub> impact

The International Energy Agency (IEA) provided the following estimates<sup>7</sup> for the year 2019

WORLDWIDE ICT ELECTRICITY CONSUMPTION 8 TO 9% OF TOTAL		
FIGURES FROM 2019 ~8.5%		
WORLDWIDE ELECTRICITY CONSUMPTION ~23500 TWH		
DATA CENTRES	~ 200	TWH
NETWORKS: INTERNET & RAN	~ 250	TWH
END USERS	~ 550	TWH
MANUFACTURING OF ICT	~ 1000	TWH
ICT ELECTRICITY CONSUMPTION	~ 2000	TWH

Table 7.2. Worldwide ICT electricity consumption

Over the last decade, ICT has substantially increased its overall share of electricity consumption, rising from 4-5% a decade ago, to 8-10% of total electricity production at the present time. Because of Covid-19, the years 2020 and 2021 are atypical when it comes to energy estimates. Translating energy consumption to GHG emissions indicates that ICT emissions are very similar to those generated from air travel<sup>8,9</sup>.

<sup>7</sup> G. Kamiya. Data Centers and Data Transmission Networks. International Energy Agency, Paris, June 2020, <https://www.iea.org/reports/data-centers-and-data-transmission-networks>

<sup>8</sup> E. Gelenbe and Y. Caseau, "The impact of information technology on energy consumption and carbon emissions", ACM Ubiquity Vol. 15, Issue June, Article 1, pp. 1-15, <https://doi.org/10.1145/2755977>

<sup>9</sup> Assoc. for Comp. Machinery Tech. Council: <https://dl.acm.org/doi/pdf/10.1145/3483410>

Certain ICT industry sectors privilege the purchase of energy from low-carbon sources to improve their CO<sub>2</sub> emissions. Although this encourages electric power producers to increase their low-carbon energy supplies, it can also encourage the production or transfer of non-low-carbon energy sources in or into other sectors of the economy – or neighbouring countries.

Canada, which produces almost 60% of its electricity from low-carbon sources such as hydroelectricity or wind and solar power, is an interesting example. On the one hand, some of this energy is used to extract the shale gas and oil it subsequently exports. On the other hand, it also exports hydroelectric energy to the United States of America. While this leaves some internal sectors depending on non-low-carbon sources, it also improves the type of energy consumed in the United States. For instance, in a 2015-2030 prospective study<sup>10</sup> on increasing data centre demand in the country, it was found that covering that demand by reducing hydroelectric exports may force the US to increase its own non-low-carbon electricity generation, suggesting the need for optimisation at a global level.

Carbon emissions per kWh of electricity vary widely from one country to another depending on the primary sources of energy that are used. Countries such as Belgium and France, that generate most of their electricity from nuclear plants, have a very low average CO<sub>2</sub> emission – well under 100g per kWh of electricity.

A further and seldom mentioned environmental concern regarding ICT is that digital chips currently use nearly two-thirds of the elements of the periodic table, many of which require energy to extract and can also be pollutants when ICT equipment is being decommissioned.

#### 1.4. The effects of evolving technologies

Since its origin in the 1940s, ICT research and industry have constantly pursued and achieved higher levels of performance, greater processing speeds, and faster data transmission rates. These advances have been accompanied by a constant increase in the penetration of ICT into all sectors of society and the economy and generally offered great gains in social welfare. However, this has also been accompanied by a steady increase in associated energy consumption and GHG emissions by ICT.

Two current significant technology evolutions result in further increases in ICT energy consumption:

- the adoption of 5G standards for mobile networks
- the increasing use of Edge computing (Fog architecture – at the edge of the cloud)

Both of these transitions are good examples of the manner in which ICT energy consumption evolves. The Global System for Mobile Operators Association (GSMA) indicates that 20% to 40% of the operating expenses of network operators are currently for electricity, and that 5G may cause a substantial (as much as by 4- to 5-fold) increase of energy consumption in the Radio Access Network (RAN) in the first instance.

Later generations of 5G technology may well include technical advances to reduce this increase in energy consumption<sup>11</sup>. However, this is still a matter for research.

The expansion of Fog and Edge devices, that accompany the penetration of 5G to meet the low latency needs of mobile applications by making large data sets and video available in the proximity of mobile base stations, is also a potential source of increased electricity consumption. Edge equipment, however, also partially duplicates the Cloud, since safe permanent repositories in the Cloud are also needed. We may therefore expect the electricity needed to operate and manufacture the additional Edge equipment to come over and above some of the electricity consumption that would anyway be used to operate and manufacture Cloud servers.

On the other hand, more frequent short-haul data transfers between Edge devices and user mobile devices, to replace long-haul transfers with the Cloud, may well save “operating” electricity in the network.

An undisputed source of recent electricity consumption increase by ICT is the expansion of cryptocurrency (including both “mining” and sales), and more generally the use of ‘blockchain’ or distributed ledgers for securing contractual agreements. These technologies rely crucially on large numbers of concurrent distributed transactions in thousands of servers. They generate intensive traffic and millions of such distributed transactions in servers.

<sup>10</sup> T. Dandres, N. Vandromme, G. Obrekht, A. Wong, K.K. Nguyen, Y. Lemieux, M. Cheriet and R. Samson, “Consequences of Future Data Center Deployment in Canada on Electricity Generation and Environmental Impacts. A 2015-2030 Prospective Study”. *Journal of Industrial Ecology*, vol 21, n.5, 2016.

<sup>11</sup> GSMA. Energy Efficiency. <https://www.gsma.com/futurenetworks/wiki/energy-efficiency-2/>

Recent reports<sup>12, 13</sup> agree on current estimates of electricity consumption for this activity of the order of 120 TWh per year – more than the electricity consumption of a small but advanced country, such as the Netherlands. Yet another recent trend, namely the increased usage of Machine Learning or “AI” in a greater number of applications, is a source of energy intensive large-scale and high-speed computations. As an example, a recent study shows that one single machine learning based training set of a specific natural language software processor can produce as much CO<sub>2</sub> emissions as five “average” conventional cars during their lifetimes<sup>14</sup>.

As a result of these developments, it will be hard to expect a flattening of the energy curve for ICT in the coming few years, and the potential impact of futuristic Quantum Computing technologies is still difficult to evaluate.

However, there are several approaches that can help achieve electricity savings in ICT:

- Increased use of “Sleep Cycles” and slower operation when feasible.
- Optimum equipment replacement policies, including the greater use of repairs and upgrades rather than the total replacement of older equipment.
- Real time control of important system procedures, such as network paths and computer loads, which might deliver better trade-offs between power consumption and quality of service (QoS)<sup>15</sup> as shown in Fig. 7.3.

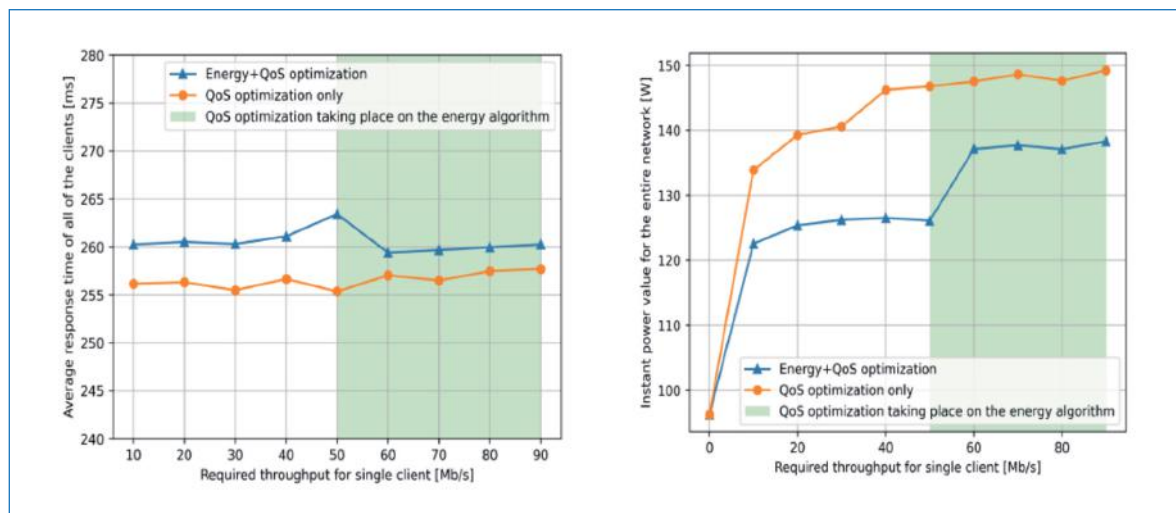


Fig. 7.3. Adaptation with reinforcement learning reduces power consumption by 10-15% at a cost of 2% reduction in average response time<sup>16</sup>

## 2. Data centres: the special perspective provided by the Irish experience

### 2.1. Background

Ireland is a small country (Peak annual power demand <7GW). Economic development in the country has been driven for many years by overseas high-tech investment, particularly from US companies such as Microsoft, Intel, Google, Amazon, Facebook, etc.

Ireland’s power industry has been perceived as delivering a reliable if somewhat expensive service. The power system is lightly connected to the UK power system. Generation is currently primarily gas fired. Coal fired generation is scheduled for phase out within five years. There has been a swift expansion in onshore wind generation over the past decade. A further rapid increase in offshore wind energy is planned for the coming decade but these plans may be unrealistic.

<sup>12</sup> Assoc. for Comp. Machinery Tech. Council: <https://dl.acm.org/doi/pdf/10.1145/3483410>

<sup>13</sup> <https://www.moneysupermarket.com/gas-and-electricity/features/crypto-energy-consumption/>

<sup>14</sup> <https://www.technologyreview.com/2019/06/06/239031/training-a-single-ai-model-can-emit-as-much-carbon-as-five-cars-in-their-lifetimes/>

<sup>15</sup> E. Gelenbe, J. Domanska, P. Fröhlich, M. P. Nowak and S. Nowak. “Self-Aware Networks that Optimize Security, QoS, and Energy”, Proceedings of the IEEE, vol. 108, no. 7, pp. 1150-1167, July 2020, doi: 10.1109/JPROC.2020.2992559

<sup>16</sup> P. Fröhlich, E. Gelenbe, J. Fiolka, J. Checinski, M. Nowak, and Z. Filus “Smart SDN Management of Fog Services to Optimize QoS and Energy”, Sensors Vol. 21 (<https://doi.org/10.3390/s21093105>), p. 3105, MDPI, 2021

The current decarbonisation target for the power industry is set at 80% low-carbon generation by 2030. Little credible planning currently underpins this target.

## 2.2. Data centres

Data centres began to emerge as a major load on the Irish system six years ago. There are two drivers for this:

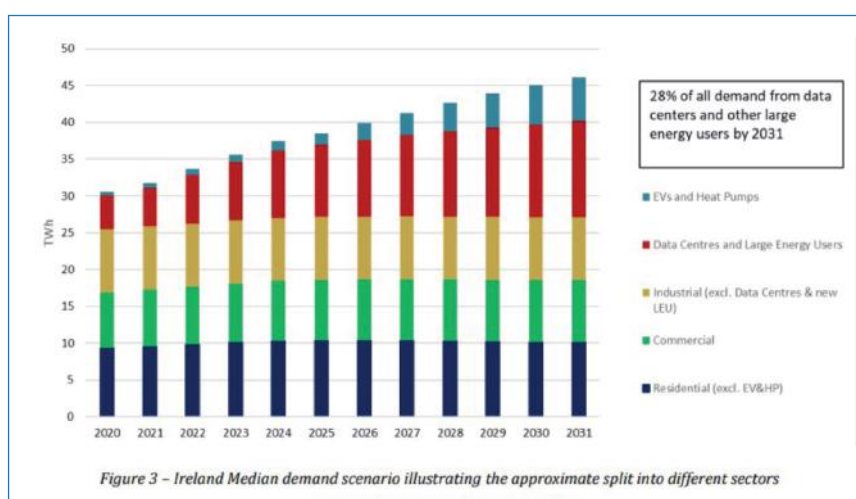
- Existing presence of many European HQs for high tech companies;
- Relative low cost of connection. The cost of deep network reinforcement is socialised in Ireland and the grid company (EirGrid) is required to service any arising demand.

This has led to a significant requirement for new transmission investment. Such investment is socially opposed almost everywhere. There is virtually no prospect of locating further large loads in the area of Dublin, the capital of Ireland, where most of the existing data centres are already located.

The problem of power supply to new data centres was first identified by the Irish Academy of Engineering in 2019<sup>17</sup>. The issue has become highly politicised in Ireland with many calls for a halt to data centre expansion. Industrial policy continues supporting data centre expansion for existing large multinational tech investors.

One of the most recent data centres is configured for the Chinese Company, Byte Dance, to support its TikTok app. The capital investment is estimated at EUR 420 million and the plant will have a power demand of 60 MW<sup>18</sup>. It is only one of a number of such projects.

The National Transmission System Operator, EirGrid, has recently produced demand projections showing a rapid expansion of electricity demand by 2030, almost all of which is due to data centre expansion. It estimates that under a median expansion scenario 28% of Irish electricity demand would originate from data centres by 2031. More aggressive projections show a possible 31% increase by 2027.



**Fig. 7.4.** Annual demand split by sectors, per year (extract from EirGrid report “Ireland Capacity Outlook 2022-2031 October 2022”) [https://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid\\_SONI\\_Ireland\\_Capacity\\_Outlook\\_2022-2031.pdf](https://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid_SONI_Ireland_Capacity_Outlook_2022-2031.pdf)

The problems in the Dublin area are primarily due to a lack of power transmission capacity. These problems cannot be solved in the short or medium term and quite possibly not even in the long term.

New regulations have recently been issued by the Irish Commission for Regulation of Utilities (CRU)

- No further data centres will be permitted in the Dublin area (existing applications will be processed)
- Data centre standby generation must be made available in the event of any arising supply problems. EirGrid may disconnect centres at 1 hours’ notice.
- Future data centres will be permitted where they can be easily accommodated on the transmission network.

<sup>17</sup> <http://iae.ie/wp-content/uploads/2019/08/Data-Centres-July-2019.pdf>

<sup>18</sup> Tik Tok to open €600m European data centre in Ireland ([irishtimes.com](https://www.irishtimes.com))

### 2.3. Generation issues

In addition to localised transmission issues, there are major questions over the requirement for new generation to meet increased demand at a time when Ireland has adopted a very ambitious decarbonisation policy for its power industry.

The Government has adopted a formal annual target of 80% low-carbon generation (mainly wind) by 2030. Ireland already has the highest System Non-Synchronous Penetration (SNSP) in the world - a significant achievement by a semi-isolated power system. As the country moves towards an 80% low-carbon target, the technical barriers become higher and higher and both resilience and adequacy risks increase.

The data centre industry has expressed a willingness to engage with large-scale low-carbon investors (by way of power purchase agreements) as a show of support for Government policies. The Irish Academy of Engineering (IAE) does not understand how such agreements will assist in reaching decarbonisation goals over the next decade.

### 2.4. Recent developments

The war in Eastern Europe has impacted all of Europe's energy industries. Ireland's power industry is no exception. Prices have risen rapidly because of primary fuel price increases. This is now a major economic and political issue, as indeed it is in the rest of Europe.

Ireland does not have Liquefied Natural Gas (LNG) import facilities and lacks any large-scale gas storage facilities. Therefore, it does now seem likely that the planned shutdown of Ireland's 900 MW coal fired generating plant at Moneypoint in 2025 will not proceed; this plant may well operate for a further 5 years beyond its planned shutdown date.

Plans are being prepared to ration gas supplies if necessary and switch a number of gas-fired generating units to distillate fuel. The IAE has recently published a short advisory report on the emergency measures that may be required<sup>19</sup>.

There continues to be a fundamental contradiction between Ireland's support for data centre expansion (a matter of industrial development policy) and Ireland's highly ambitious (if perhaps unrealistic) decarbonisation targets.

Proposals for 'Corporate power purchase agreements' between data centres and low-carbon energy producers have been put forward as a solution. The Academy does not agree with this solution and perceives such arrangements as providing perhaps 40% of data centre power requirements from low-carbon sources with the balance being provided from conventional carbon emitting generators.

A recent publication from the Long Duration Energy Storage Council (LDES) and McKinsey offers a useful perspective on such arrangements<sup>20</sup>.

<sup>19</sup> <http://iae.ie/publications/europes-energy-crisis-implications-for-ireland/>

<sup>20</sup> <https://www.dropbox.com/s/mka9fjowc0lffkw/net-zero-power-long-duration-energy-storage-for-a-renewable-grid.pdf?dl=0>

### 3. Key message and recommendations

While the environmental impact of other industries has been an object of studies and serious concern for decades, the CO<sub>2</sub> impact of the ICT industry has only surfaced in recent years due to the pervasiveness of the internet and wireless technology in society, and to ICT's share – close to 10% and growing – in electricity consumption worldwide.

Because of the complexity of telecommunication and computer networks, without the availability of expert knowledge, it is difficult to understand the interactions between applications, usage, infrastructure, and energy consumption. Moreover, because ICT enjoys a positive, even ludic reputation among users, and because it fulfils society's essential need for efficient communications, the sector is rarely considered a polluter in the eyes of governments and the general public – quite the opposite: ICT is often proposed as a major solution to bypass the environmental impact of other sectors such as aviation and transport.

#### Key message

ICT is and will continue to be a great enabler for societal improvements and for reducing the environmental impact of other sectors. However, as we learned from the COVID crisis, society increasingly depends on the performance and developments of ICT, while the world's most developed economies include many nations that are both the most advanced in ICT deployment and emit the most GHG.

Indeed, continued exponential growth in the ICT sector brings along the 'smartness everywhere' trend, the extensive Internet of Things (IoT), new applications such as the metaverse, the pervasiveness of Artificial Intelligence algorithms, and the popularisation of cryptocurrency. As these add to our everyday lives, they carry a heavy price in terms of ICT energy consumption and CO<sub>2</sub> emissions. Governments, industries and experts should thus start paying close attention to the trade-off solutions that are needed for a successful and sustainable ICT sector to develop.

Given the current status and the likely evolution of the ICT sector, the recommendations in this chapter focus on what we consider to be the four most relevant issues on the basis of their long-term impact: data centre energy consumption, 5G expansion, Edge computing, and the need for improved ICT energy consumption metrics without forgetting the optimal replacement of ICT equipment to reduce the emissions on their lifecycle.

#### Recommendations

##### 3.1. Data centre energy consumption

Power Usage Effectiveness (PUE) is a metric used to determine the energy efficiency of a data centre. PUE is obtained by dividing the total amount of power entering a data centre by the power used to run the IT equipment within it. PUE has been steadily falling for the past decade but, despite this, overall data centre energy consumption has been increasing as expansion in facilities outpaced efficiency improvements. There is wide variability in the data centre GHG emissions depending on the source of electric supply. Emissions from data centres supplied by hydroelectric or nuclear power will be orders of magnitude lower than from similar facilities supplied by fossil fuel-based electricity.

Recent reports indicate that efficient management, including the judicious repair and upgrade of existing equipment within data centres, may greatly increase the overall energy efficiency of a facility. Effective management practices are considered to halve overall energy usage in certain situations.

Therefore, we recommend:

- deferring data centre machine computations in time to favour load shifting, load sharing, peak energy shaving and maximum use of low-carbon sources of electricity;
- further efforts to improve data centre PUE;
- minimising unnecessary data centre operations; repairing and upgrading equipment rather than replacing it whenever possible.

### 3.2. Energy consumption of 5G technology and beyond

5G cellular network technology is now being deployed on a global scale. Such a deployment is expected to accelerate in the short term. The energy consumption of a 5G base station is 2 to 3 times higher than that of a similar 4G installation providing the same coverage area. Moreover, in shorter wavelengths base stations up to 25 microns, several 5G base stations will be required to cover an area similar to a single 4G base station. This implies a significant increase in energy consumption for a similar coverage area.

Given this reality, we recommend that:

- there should be active energy management of base stations, and it should be integrated into the optimisation planning<sup>21</sup> to provide slack for future energy efficient operation;
- 5G operators should share infrastructure and reduce the duplication of energy consumption;
- infrastructure providers should interact with electric utilities to reduce the CO<sub>2</sub> impact of the electricity provided to 5G base stations and also help in peak shaving;
- Research should attempt to improve the energy efficiency of 5G devices and transmissions, and a relevant PUE-type metric should be introduced to benchmark different systems.

### 3.3. Edge computing

Edge computing is a technology that reduces network communications by installing data processing and storage close to the user. It drastically reduces latency for stringent 5G applications such as connected cars, games or videos, and also reduces long-haul data transfers that use large amounts of energy. However, it also leads to the addition of numerous small data centres that do not fully replace the Cloud, but do not benefit from the energy optimisation of large-scale facilities.

The following steps are recommended:

- Carry out further research to clarify the performance, energy consumption and GHG emission trade-offs between Edge systems and Cloud servers. This is particularly important in the context of new applications that exploit 5G, future 6G, Edge and Cloud systems.
- Develop appropriate PUE-type metrics for future integrated edge computing and data centre-based systems. These should be related to the low latency and high-volume data transfer aspects of future architectures.

### 3.4. ICT energy and CO<sub>2</sub> statistics

It is notoriously difficult to find reliable and specific data to assess the energy consumption of ICT at large<sup>22</sup> and of specific technologies or applications. In some cases, available data remains confidential to a few stakeholders. The lack of standardisation additionally causes difficulties in making valid comparisons. Unless these issues are addressed, it will remain extremely difficult to reach valid conclusions on the impact of ICT on GHG emissions. The following is recommended:

- Set public requirements and standards for the compilation, retention and publication of ICT energy consumption and GHG emissions data.

### 3.5. Optimal replacement of ICT Equipment to Improve its Environmental Impact

Since energy consumption for manufacturing of ICT represents 50% of the total, and because of the high environmental impact of ICT decommissioning, it is important to develop judicious policies about when to decommission existing operational equipment, or replace it by other equipment to achieve improved energy efficiency, better performance and reliability. Decommissioned equipment may often be repaired, enhanced and used in different useful contexts.

<sup>21</sup> S. Boiardi, A. Capone and B. Sansò, "Planning for energy-aware wireless networks", in *IEEE Communications Magazine*, vol. 52, no. 2, pp. 156-162, February 2014, doi: 10.1109/MCOM.2014.6736757

<sup>22</sup> ACM TechBrief: Computing and Climate Change, ACM Technology Policy Council, Issue 1, November 2021

## Abbreviations, definitions and acronyms

---

<b>5G</b>	The fifth-generation technology standard for broadband cellular networks
<b>Cloud</b>	Cloud computing is a general term for anything that involves delivering hosted services over the internet
<b>CRU</b>	Irish Commission for Regulation of Utilities
<b>Edge computing</b>	Distributed computing paradigm that brings computation and data storage closer to the sources of data
<b>EirGrid</b>	The Irish National Electricity Transmission System Operator
<b>FOG computing</b>	Also called Edge computing
<b>GHG</b>	Greenhouse Gas
<b>ICT</b>	Information and Communications Technologies
<b>IEA</b>	The International Energy Agency, based in Paris, France
<b>LNG</b>	Liquefied Natural Gas
<b>LTE</b>	Long-Term Evolution, is a standard for wireless broadband communication for mobile devices and data terminals
<b>NUC</b>	Network Unit of Computing
<b>PUE</b>	Power Usage Effectiveness
<b>RAN</b>	Radio Access Network
<b>IoT</b>	Internet of Things

---

## CHAPTER 8. CONCLUSIONS

Chapter prepared by **Yves Bamberger** and adopted by the Energy Committee

There is ample and indisputable scientific evidence that global GHG emissions are continuing to increase. The levels of the major greenhouse gases in the atmosphere, namely carbon dioxide and methane, are still rising. Humanity is progressing very slowly towards the implementation of the Paris Agreement and meeting the United Nations Sustainable Development Goals (SDGs), such as reducing poverty.

**The CAETS Energy Committee is aware of the many difficulties and conflicting interests involved in moving the world faster towards fewer GHG emissions.**

To have a global impact, any significant transition requires a long time to be achieved. Moreover, major transitions are implemented at different paces, using different models across different regions and countries. The required transition to a sustainable world – progressively reducing and then reversing the increase of GHGs in the atmosphere, while mitigating the ongoing impacts of global warming and meeting the SDGs – is a challenge of unprecedented proportions for humanity.

The committee does not underestimate the many intertwined and in some cases contradictory challenges ahead. The world's existing fossil fuel-based industrial infrastructure represents trillions of dollars of investment, and existing large facilities have viable economic life spans of decades. An effective transition will need to retrofit such existing infrastructure by modifying the many thousands of industrial facilities that have been optimised for efficiency and economic returns, as well as replacing some or building new ones. At the same time, retrofitting the homes and buildings where billions of people live and constructing sustainable new ones is an enormous challenge.

Furthermore, there is a need for scaling up the industries necessary for this transition, to provide them with the required new skills and coherent ecosystems in particular. This necessitates sustainable public buy-in and massive investments with adapted regulations and policies.

**The CAETS Energy Committee, through its 2022 Energy Report, wishes to emphasise that many technologies designed to reduce – and in some cases almost eliminate – GHG emissions are already available for immediate action in the key sectors.** The 7 sector-specific chapters of this report have described some of such 'low-hanging fruit' with rapid (from a few months to a few years) payback times and reasonable returns on investment, as well as other solutions that are affordable or could be made so for large-scale deployment, provided clear, predictable public policies (regulations, incentives, taxes, and so on) providing scope for public and private investments are established.

Technologies for immediate action are indeed available. The difficulty lies in implementing them fast and at affordable costs, in a way that is tailored to each country and region in each sector of activity. This will not be possible without long-lasting support from governments and, last but not least, consumers and citizens.

The committee has thus focused on available technologies that can provide results now and for the next twenty years. Some of these technologies are already deployable while others are near-to-deployment promising technologies. These technologies allow very significant emission reductions. However, we keep on stressing the importance of supporting RD&D and developing interaction between universities and engineering companies, to improve existing technologies and promote the development of new ones, thus providing opportunities to explore potentially new, easier and shorter paths to succeed in globally reducing our GHG emissions by the middle of the century. In a future report, the Energy Committee of CAETS will focus on these longer-term issues.

Nevertheless, there is no time to waste before starting the deployment of available technologies and cutting their costs through scale and incremental innovation. Our key findings to boost faster and lower-cost innovation can be summarised in the five following points.

**The first point to consider is the idea of ‘systemic’ or ‘holistic’ approaches.** Such approaches break away from the traditional ‘silo’ mentality and practices. Silos are indeed vertical structures. On the contrary, national and local administrations, as well as company affiliates, must work together to reduce GHG emissions to ensure consistency between their actions: it will facilitate and accelerate implementation while reducing costs.

One example of a holistic approach is the rapid deployment of heat pumps to reduce the use of energy and lower GHG emissions from heating and cooling. This requires indeed sufficient industrial capacity, appropriate state or local regulations with quality labels, knowledgeable architects, engineers and promoters, and also competent local installers. Similarly, a holistic approach will benefit the evolution of technologies and products needed to transform global agriculture according to a less-intensive GHG model. This will require transformations in the global chemical industry, which, in turn, is closely linked to the oil and gas industry. At the same time, farmers and their professional practices are key to achieving these transformations as initiated by new regulations. Cooperation between industries, e.g., the cement industry working with the petroleum industry to sequester CO<sub>2</sub> for example, is another aspect of such a systemic approach.

Holistic transformations need to take into account the consequences of the choices made outside of each specific sector: initiatives that overlook rebound effects elsewhere will not guaranteed to lower global GHG emissions. For this endeavour, Life Cycle Assessment (LCA) models should be more widely and more precisely used by public and private stakeholders. LCA can help stakeholders identify more cost-effective and more significant transformations through the analyses they required.

**The second point** is that the various economic sectors we have covered will need to use more electricity to reduce emissions. This measure will generally and at the same time increase energy efficiency.

To reap the full benefits of electrification, such electricity will have to be low-carbon, i.e. mostly produced from hydropower, wind, solar and nuclear energy. In some cases, where the direct use of electricity is not possible, emissions will be reduced through the use of hydrogen produced from low-carbon electricity.

A key issue, which has remained outside the scope of this report, **will be to ensure the availability of sufficient and affordable low-carbon electricity for the next decades**, which requires stable and consistent policies (in particular for cost control) and the implementation of ways of matching patterns of supply to patterns of demands, through storage and end-use flexibility.

**A third point** came up in the discussions of each sector and of the whole CAETS Energy Committee: **putting emphasis on education and training, in particular in technology and engineering.**

One aspect is to develop the skills of those who already work in these sectors and accompany them as needed in the transition. At a higher speed than in the past, new jobs will appear, and some others will disappear or will be deeply transformed, and not only by digitalisation. The coming period is one where retraining needs to be facilitated.

A second aspect is to adapt the world of education and training to prompt transformation to a low-GHG society – this applies to new but also to “traditional” jobs, which should not be forgotten and will remain, even transformed, such as for example mining, heavy industry, or agriculture. Upstream, the issue of training teachers at all levels, from primary schools onwards, needs also to be addressed.

This is also an opportunity for Schools of Engineering and Technologies to rethink and develop their role.

Another issue on education and training concerns the decision-makers, especially the politicians: how should they be prepared for these holistic approaches and also for organising and leading such transformation projects?

**The fourth point**, which is not detailed in our report, is connecting with **citizens and public opinion**. This critical connection, which is essential for the sustainable acceptance of the changes allowing for lower GHG solutions, will differ considerably from country to country across the globe. Although there has been much progress in reducing global poverty, the acceptable solutions, and even the time trajectories towards their acceptance, will vary significantly between developed and developing nations, as between rich and people. The issue of education is always key, even more so with the development of social networks and fake news.

**The final point**, linked to the professional experience of the Committee members, is the importance of scientific and technological **interactions**, the sharing of good practices, and cooperation between governments, industry and academia, both nationally and internationally. All the above transformations, which imply major projects, raise the question of how decision-makers, especially policy makers and leaders from industry, can involve those who are knowledgeable, from the academic world and from industry, to achieve such projects. The CAETS and its Members in the different countries are ready to intensify their contribution to these transformations.

**We, the Members of the Committee, are strongly emphasising that**, beyond the RD&D, which is essential to tackle climate change, existing and future technology deployments should be based on enlightened policies, appropriate funding and robust public and private support, as well as accurate information and sound logic, to allow us and our children to protect our common planet Earth and its ecological heritage.

# LIST OF PARTICIPANTS

## AUTHORS

---

**ADESINA Adesoji A.**, Nigeria, *Nigerian Academy of Engineering (NAEng)*

**ALBARRÁN-NUÑEZ Jose Francisco**, Mexico, *Mexican Academy of Engineering (AI)*

**ALVAREZ PELEGRY Eloy**, Spain, *Royal Academy of Engineering (RAI)*

**ANYAEJI Otis**, Nigeria, *Nigerian Academy of Engineering (NAEng)*

**AVIDAN Amos**, United States, *National Academy of Engineering (NAE)*

**BAMBERGER Yves**, France, *National Academy of Technologies of France (NATF)*

**BANDYOPADHYAY Bibek**, India, *Indian National Academy of Engineering (INAE)*

**BEHRENDT Frank**, Germany, *National Academy of Science and Engineering (acatech)*

**BERTERO Raúl**, Argentina, *National Academy of Engineering (ANI)*

**BRAVO LÓPEZ Manuel**, Spain, *SECOT (Spanish Seniors for Technical Cooperation)*

**CAI Rui**, China, *Chinese Academy of Sciences (CAS)/ Dalian Institute of Chemical Physics (DICP)*

**CARNICER Roberto S.**, Argentina, *National Academy of Engineering (ANI)*

**CARON Patrick**, France, *University of Montpellier, Centre for International Cooperation in Agricultural Research for Development (CIRAD)*

**CATALDO José**, Uruguay, *National Academy of Engineering (ANIU)*

**CHAKRABORTY Sudhansu Shakhar**, India, *Indian National Academy of Engineering (INAE)*

**CHANG Woong-Seong**, Republic of Korea, *National Academy of Engineering of Korea (NAEK)*

**CHATURVEDI Pradeep**, India, *Indian National Academy of Engineering (INAE)*

**COKER Olufunmi**, Nigeria, *Nigerian Academy of Engineering (NAEng)*

**DOMINGUEZ ABASCAL Jaime**, Spain, *Royal Academy of Engineering of Spain (RAI)*

**DOMÍNGUEZ ABASCAL José**, Spain, *Royal Academy of Engineering of Spain (RAI)*

**DUGGAN Gerry**, Ireland, *Irish Academy of Engineering (IAE)*

**DUIC Neven**, Croatia, *Croatian Academy of Engineering (HATZ)*

**EVANS Robert**, Canada, *Canadian Academy of Engineering (CAE)*

**FERREÑO Oscar**, Uruguay, *National Academy of Engineering (ANIU)*

**FINCH Nigel**, United Kingdom, *Institution of Agricultural Engineers (IAgrE)*

**FREDENBERG Lennart**, Sweden, *Royal Swedish Academy of Engineering Sciences (IVA)*

**FRITZ DE-LA-ORTA Erwin**, Mexico, *Mexican Academy of Engineering (AI)*

**FU Lin**, China, *Tsinghua University*

**GAO Kunlun**, China, *State Grid Smart Grid Research Institute Co. Ltd.*

**GELENBE Erol**, France, *National Academy of Technologies of France (NATF)*

**GEHRISCH Wolf**, France, *National Academy of Technologies of France (NATF)*

**GIOVAMBATTISTA Alberto**, Argentina, *National Academy of Engineering (ANI)*

**GODEFROY Julie**, United Kingdom, *CIBSE & Member of UK National Engineering Policy Centre Working Group on Systems Approaches to Net Zero*

**HASLETT Andrew**, United Kingdom, *Royal Academy of Engineering (RAEng)*

**HEFFT Daniel**, United Kingdom, *Institution of Agricultural Engineers (IAgrE)*

**HOFMANN-SIEVERT Rita**, Switzerland, *Swiss Academy of Engineering Sciences (SATW)*

**HOLZNER Christian**, Switzerland, *Swiss Academy of Engineering Sciences (SATW)*

**HU Shan**, China, *Tsinghua University*

**IGWE Godwin J.**, Nigeria/United States, *Nigerian Academy of Engineering (NAEng)*

**IMASOGIE Benjamin**, Nigeria (passed away), *World Bank McNamara Fellow/Nigerian Academy of Engineering (NAEng)*

**JIANG Yi**, China, *Chinese Academy of Engineering (CAE), Tsinghua University*

**Elsabe KEARSLEY**, South Africa, *South African Academy of Engineering (SAAE)*

**LANGLAIS Catherine**, France, *National Academy of Technologies of France (NATF)*

**LIEUWEN Timothy**, United States, *National Academy of Engineering (NAE)*

**MATLOSZ Michael**, France, *National Academy of Technologies of France (NATF)*

**MEISEN Axel**, Canada, *Canadian Academy of Engineering (CAE)*

**MELVIN Christopher**, United Kingdom, *Institute of Materials, Minerals & Mining (IOM3)*

**MESAROVIC Miodrag**, Serbia, *Academy of Engineering Sciences of Serbia (AESS)*

**MORILLÓN David**, Mexico, *Mexican Academy of Engineering (AI)*

**MOULLEC Gaël-Georges**, France, *National Academy of Technologies of France (NATF)*

**O'BRIEN Kieran**, Ireland, *Irish Academy of Engineering (IAE)*

**OKE Clement**, Nigeria, *Nigerian Academy of Engineering (NAEng)*

**OLIVIER-BOURBIGOU Hélène**, France, *National Academy of Technologies of France (NATF)*

**PARK Chinho**, Republic of Korea, *National Academy of Engineering of Korea (NAEK), Korea Institute of Energy Technology*

**PÁTZAY György**, Hungary, *Budapest University of Technology and Economics*

**REINDERS Felix**, South Africa, *South African Academy of Engineering (SAAE)*

**SANSO Brunilde**, Canada, *Polytechnique Montréal, Department of Electrical Engineering*

**SCOTT Norman Roy**, United States, *National Academy of Engineering (NAE)*

**SOHN II**, Republic of Korea, *National Academy of Engineering of Korea (NAEK), Yonsei University*

**SPEER John**, United States, *National Academy of Engineering (NAE)*

**TANGUY Philippe A.**, Canada/France, *Canadian Academy of Engineering (CAE)*

**VIGNART Oscar**, Argentina, *National Academy of Engineering (ANI)*

**WAGNER Ulrich**, Germany, *National Academy of Science and Engineering (acatech)*

**WANG Yishen**, China, *State Grid Smart Grid Research Institute Co. Ltd.*

**WRIGHT Dave**, South Africa, *South African Academy of Engineers (SAAE)*

**WU Yanting**, China, *Tsinghua University*

## OTHER CONTRIBUTORS

---

**ASZODI Attila**, Hungary, *Hungarian Academy of Sciences (MTA)*

**CHU Mansheng**, China, *Northeastern University*

**DE BOER Rebecca**, United States, *The National Academies of Sciences, Engineering, and Medicine (NASEM)*

**GUARGA Rafael**, Argentina, *National Academy of Engineering (ANI)*

**HERCE Carlos**, Italy, *ENEA*

**HILL Jason**, United States, *University of Minnesota, Dpt. of Bioproducts and Biosystems Engineering*

**KIM Kisoo**, Republic of Korea, *POSCO, Low Carbon Process Research Lab.*

**KUBOYAMA Jun**, Japan, *METI*

**MIKULČIĆ Hrvoje**, Croatia, *University of Zagreb*

**MOTHERWAY Brian**, Ireland, *International Energy Agency (IEA)*

**UNNIKRISHNAN M.S.**, India, *IITB-Monash Research Academy, Indian National Academy of Engineering (INAE)*

**NEVICATO David**, France, *TotalEnergies SE*

**OCHSNER SEN Karl**, Austria, *OCHSNER Wärmepumpen GmbH*

**OGBUGWE Anthony**, Nigeria, *Nigerian Academy of Engineering (NAEng)*

**ORR Franklin M. Jr.**, United States, *Stanford University*

**PALOTÁS Árpád B.**, Hungary, *Materials and Chemical Engineering, University of Miskolc*

**PERRIE Bryan**, South Africa, *South African Academy of Engineering (SAAE), Cement and Concrete SA (CCSA)*

**SAGAR Ambuj**, India, *Indian Institute of Technology*

**SAUVION Guy-Noël**, France, *Solvay*

**SHU Yinbiao**, China, *International Electrotechnical Commission*

**SUGIYAMA Masakazu**, Japan, *University of Tokyo*

**TOMASGARD Asgeir**, Norway, *Norwegian Academy of Technological Sciences (NTVA)*

**WANG Lan**, China, *China Building Materials Academy*

**WEI Qingpen**, China, *China Building Materials Academy*

## INTERNAL REVIEWERS

---

**ANYAEJI Otis**, Nigeria, *Nigerian Academy of Engineering (NAEng)*

**ASZODI Attila**, Hungary, *Hungarian Academy of Sciences (MTA)*

**AVIDAN Amos**, United States, *National Academy of Engineering (NAE)*

**BRAVO LOPEZ Manuel**, Spain, *SECOT (Spanish Seniors for Technical Cooperation)*

**CAI Rui**, China, *Chinese Academy of Sciences (CAS)/ Dalian Institute of Chemical Physics (DICP)*

**CHAKRABORTY Sudhangsu Sekhar**, India, *Indian National Academy of Engineering (INAE)*

**CHATURVEDI Pradeep**, India, *Indian National Academy of Engineering (INAE)*

**FREDENBERG Lennart**, Sweden, *Royal Swedish Academy of Engineering Sciences (IVA)*

**HASLETT Andrew M.**, United Kingdom, *Royal Academy of Engineering (RAEng)*

**HOFMANN-SIEVERT Rita**, Switzerland, *Swiss Academy of Engineering Sciences (SATW)*

**LEVY Christophe**, France, *Holcim Innovation Center*

**LIEUWEN Timothy**, United States, *National Academy of Engineering (NAE)*

**MEISEN Axel**, Canada, *Canadian Academy of Engineering (CAE)*  
**MILFORD Rodney**, South Africa, *South African Institution of Civil Engineering (SAICE)*  
**O'BRIAN Kieran**, Ireland, *Irish Academy of Engineering (IAE)*  
**OKE Clement**, Nigeria, *Nigerian Academy of Engineering (NAEng)*  
**OROSZ Róbert**, Hungary, *Budapest University of Technology and Economics*  
**SCOTT Norman Roy**, United States, *National Academy of Engineering (NAE)*  
**VIGNART Oscar**, Argentina, *National Academy of Engineering (ANI)*

## EXTERNAL REVIEWERS

---

**APPERT Olivier**, France, *National Academy of Technologies of France (NATF)*  
**BENDER Michael**, Germany, *BASF SE, Group Research*  
**BIRÓ Bence**, Hungary, *Budapest University of Technology and Economics*  
**DEGNAN Thomas F., Jr.**, United States, *National Academy of Engineering (NAE)*  
**GREENBERG Albert**, United States, *National Academy of Engineering (NAE), Uber, VP-Platform Engineering*  
**ISAACS Eddy**, Canada, *Canadian Academy of Engineering (CAE)*  
**JONES Ceris**, United Kingdom, *Climate Change Advisor, NFU*  
**KEMP Roger**, United Kingdom, *Engineering, Lancaster University*  
**MAGDZIARZ Aneta**, Poland, *AGH University of Science and Technology*  
**MEEHAN D. Nathan**, United States, *National Academy of Engineering (NAE)*  
**MIN Dong Joon**, Republic of Korea, *National Academy of Engineering of Korea (NAEK), Yonsei University*  
**SINGH R. Paul**, United States, *National Academy of Engineering (NAE)*  
**TRYSTRAM Gilles**, France, *AgroParisTech*  
**VELEDA Carlos Alberto**, Argentina, *National Academy of Engineering (ANI)*

# ANNEXES

The annexe of this report contains two types of questionnaire responses.

The first type addresses mainly various aspects of electricity production and greenhouse gas emissions in the countries having responded. Publicly available data is mostly taken from the IEA [<https://www.iea.org/countries> and <https://www.iea.org/data-and-statistics/data-product/emissions-factors-2021#emissions-factors>]. If available, these data are then commented on by the respondents. This is followed by answers to a set of questions aimed at better defining the legal measures taken by the respective governments to achieve the 2030-2050 goals.

This first type of questionnaire responses is complemented by responses from Working-Group Members that focus on their countries' efforts made in the sectors as defined in the report.

In total, these questionnaire replies allow us to obtain a more detailed view of both the responding countries and the selected sectors.

## Note for the reader

Due to having received responses from many countries we have tried to homogenise the representation of numbers. Nevertheless, some inconsistencies will have remained. The reader may thus find 20 000 or 20,000 for twenty thousand for example. For decimal, he may find 1.23 but also 1,23 for example.

<b>Country analysis questionnaires</b> . . . . .	285
Argentina . . . . .	286
Canada . . . . .	299
Croatia . . . . .	311
France . . . . .	320
Germany . . . . .	334
Korea . . . . .	344
Mexico . . . . .	358
Nigeria . . . . .	369
Spain . . . . .	382
Sweden . . . . .	394
Switzerland . . . . .	403
United Kingdom . . . . .	423
United States . . . . .	433
<b>Sector analysis questionnaires</b> . . . . .	456
Food and agriculture . . . . .	457
Buildings and Smart Cities . . . . .	463
Oil and gas industry . . . . .	478
Chemical industry . . . . .	485
Cement industry . . . . .	488
Iron and steel industry . . . . .	512

---

# COUNTRY ANALYSIS QUESTIONNAIRES

## Table of Contents

---

<b>1.</b>	<b>National energy profile 2019</b>	287
<b>2.</b>	<b>Energy perspectives 2030 - 2050</b>	290
<b>3.</b>	<b>Building sector</b>	292
3.1.	Existing buildings	292
3.2.	New buildings	293
<b>4.</b>	<b>Industry</b>	294
4.1.	Cement Industry	294
4.2.	Chemical Industry	297

## 1. National energy profile 2019

### Total yearly consumption: final energy, electricity (TWh)

Year	Energy Consumption (TWh)	Electricity Consumption (TWh)	Electricity/ Total Energy (%)
1990	348	42.8	11.2
1995	445	58.6	13.1
2000	495	77.6	15.7
2005	551	92.9	18.0
2010	622	114.7	18.4
2015	675	136.5	20.2
2019	642	129.4	20.1

Table 1. Total yearly consumption: final energy, electricity (TWh)

The period from 1990 to 2019 is divided into three distinct stages. From a very low baseline (GDP 1990=GDP 1980 x 0.89), the first decade showed a remarkable economic growth rate. Then the 2001 crisis ensued, but the country recovered quickly and GDP resumed increasing at high rates (except for 2008-9) until 2011. In the following years, the economy stagnated until the end of the third decade considered in the above table, with years of recovery followed by years of recession. All told, the population increased by 37.3%, to 44.8 million, and GDP increased by 116%. The industrial sector grew 76%. Energy consumption increased by 84.5% and electricity consumption reached a staggering increase of 202.3%. In the latter case, the ratio of electricity consumption / total energy consumption has almost doubled in the three-decade period. Energy efficiency gains were, however, not impressive mainly because of very low domestic energy prices, disconnected for many years from international prices due to price controls, massive state subsidies and export levies.

### Total yearly consumption per person: final energy, electricity (MWh per person per year)

Year	Inhabitants (million)	Energy Consumption (TWh)	Energy Consumption per person and per year (MWh)	Electricity Consumption (TWh)	Electricity Consumption per person and per year (MWh)
1990	32.6	348	10.7	42.8	1.3
1995	34.8	445	12.8	58.6	1.7
2000	36.8	495	13.5	77.6	2.1
2005	38.9	551	14.2	92.9	2.4
2010	40.9	622	15.2	114.7	2.8
2015	43.1	675	15.7	136.5	3.2
2019	44.8	642	14.3	129.4	2.9

Table 2. Total yearly consumption per person: final energy, electricity (MWh per person per year)

GDP per capita in constant currency grew 57% over the whole period, while energy consumption per person increased by 34.2%. Electricity consumption per capita grew 120%

### Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>), total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)

Year	Total CO <sub>2</sub> Emissions (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions from electricity (MtCO <sub>2</sub> )	CO <sub>2</sub> emissions per capita
1990	93.5	18.925	2.91
1995	107.4	21.229	3.10
2000	128.0	24.424	3.50
2005	141.8	37.156	3.70
2010	162.4	42.971	4.00
2015	179.8	52.360	4.20
2019	162.2	40.052	3.60

**Table 3.** Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>), total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)

Tables are based and / or calculated from the following data

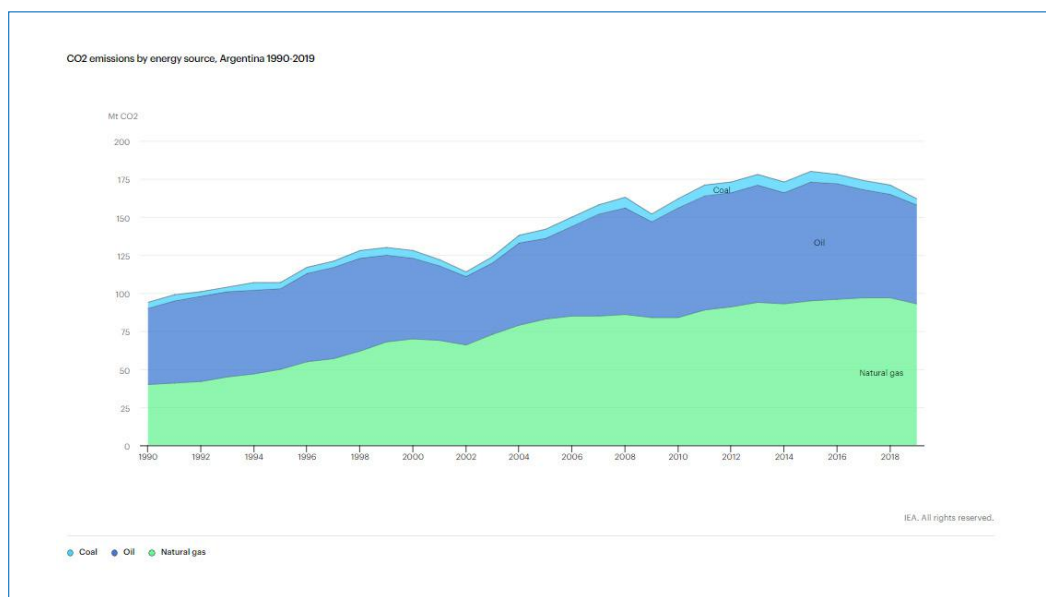
International Energy Agency - Data and statistics -Explore energy data by category, indicator, country or region

IEA (2021) Emission Factors ([https://www.iea.org/t\\_c/termsandconditions/](https://www.iea.org/t_c/termsandconditions/))

<https://www.worldometers.info/world-population/population-by-country/>

A 73.5% increase in total emissions compares to the above quoted 84.5% increase in energy consumption. In turn, a 111,6% increase in emissions from electricity generation relates to a 202.3% growth in electricity consumption. This is a strong signal of the higher efficiency of mostly natural gas-powered CCPs (Combined Cycle Power Plants) built over the 3 decades together with smaller additions in hydropower and nuclear power plants.

### CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)

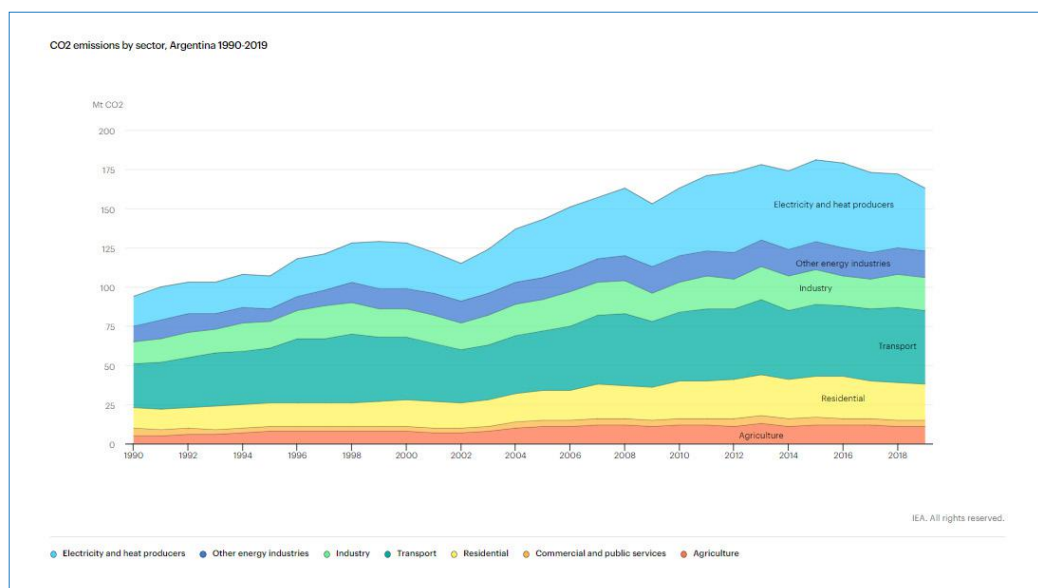


**Fig. 1.** CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)

<https://www.iea.org/data-and-statistics/data-browser?country=ARGENTINA&fuel=CO2%20emissions&indicator=CO2BySource>

Natural gas share in the energy mix has consistently remained over (and increasingly higher than) 50% for the last two decades. It displaced liquid fossil fuels for power generation and also for heating and industrial uses, having also a small share in transport (via compressed natural gas, or CNG). CO<sub>2</sub> emissions from natural gas reflect both its participation in the energy mix but also the lower level of such emissions compared to other fossil fuels.

## CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)

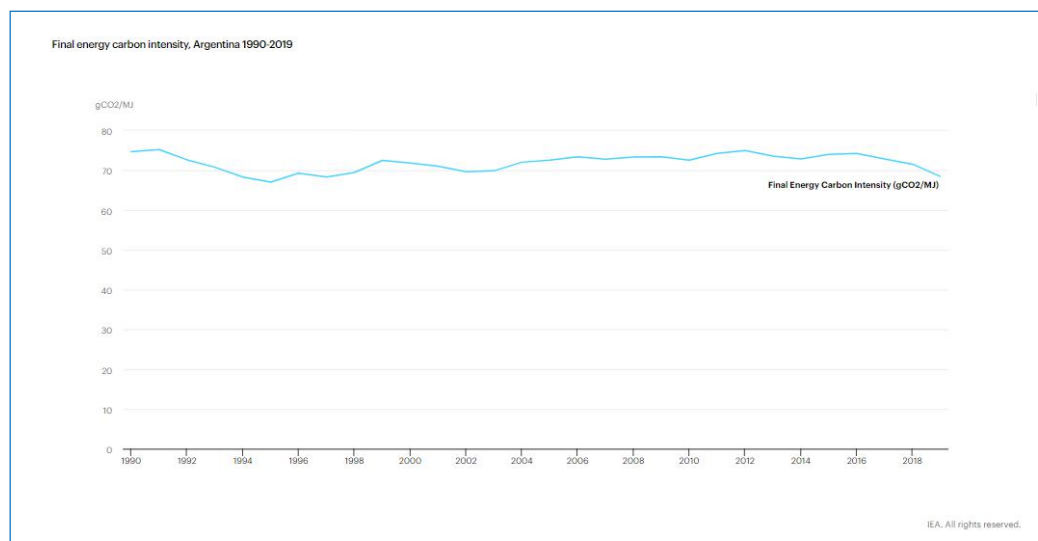


**Fig. 2.** CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)

<https://www.iea.org/data-and-statistics/data-browser?country=ARGENTINA&fuel=CO2%20emissions&indicator=CO2BySector>

In 2019, close to 49% of power generation was emissions-free (mostly hydropower, followed by nuclear and renewables). This is also reflected in the declining trend of CO<sub>2</sub> emissions, which was already observable in previous years. Transport still has an important share in emissions.

## Final energy carbon intensity: gCO<sub>2</sub>/MJ and gCO<sub>2</sub>/kWh (1 Megajoule = 0.27778 Kilowatt hours)



**Fig. 3.** Final energy carbon intensity: gCO<sub>2</sub>/MJ and gCO<sub>2</sub>/kWh  
(1 Megajoule = 0.27778 Kilowatt hours)

<https://www.iea.org/data-and-statistics/data-browser?country=ARGENTINA&fuel=CO2%20emissions&indicator=FECI>

The almost flat trend over more than two decades falls off in the last years of the third decade represented in the diagram above, and somewhat more steeply in 2019.

## 2. Energy perspectives 2030 - 2050

### Does your country have national roadmaps regarding energy production and GHG emissions? What legal status do these documents have? What is their timeline?

The Argentine Government established the actions to develop in order to mitigate GHG emissions in all sectors of the industry. This is stated in resolution 447-19 of the former Secretary of Government for the Environment and Sustainable Development of the Nation<sup>1</sup>, in its Annex V and in law 27520 of 2019<sup>2</sup>. These actions are recommended individual initiatives, which do not constitute a true 'road map'.

#### Roadmap for the energy mix

None

#### Roadmap for the GHG emissions (country, per capita)

In December 2020, Argentina submitted a second Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC). In this NDC, it undertakes to continue the reduction of emissions. By 2030, these will be reduced by 25.7% compared to the first NCD. Argentina's net emission will not exceed 359 MtCO<sub>2</sub> in 2030, applicable to all sectors of the economy. Interest in developing a strategy to achieve CO<sub>2e</sub> neutrality by 2050 was also announced.

#### Roadmap for the electricity mix

There is a 2025 target for new Renewable Energies, supplying at least 20% of the electricity demand. It was established by Law 27.191 enacted in 2015<sup>3</sup>.

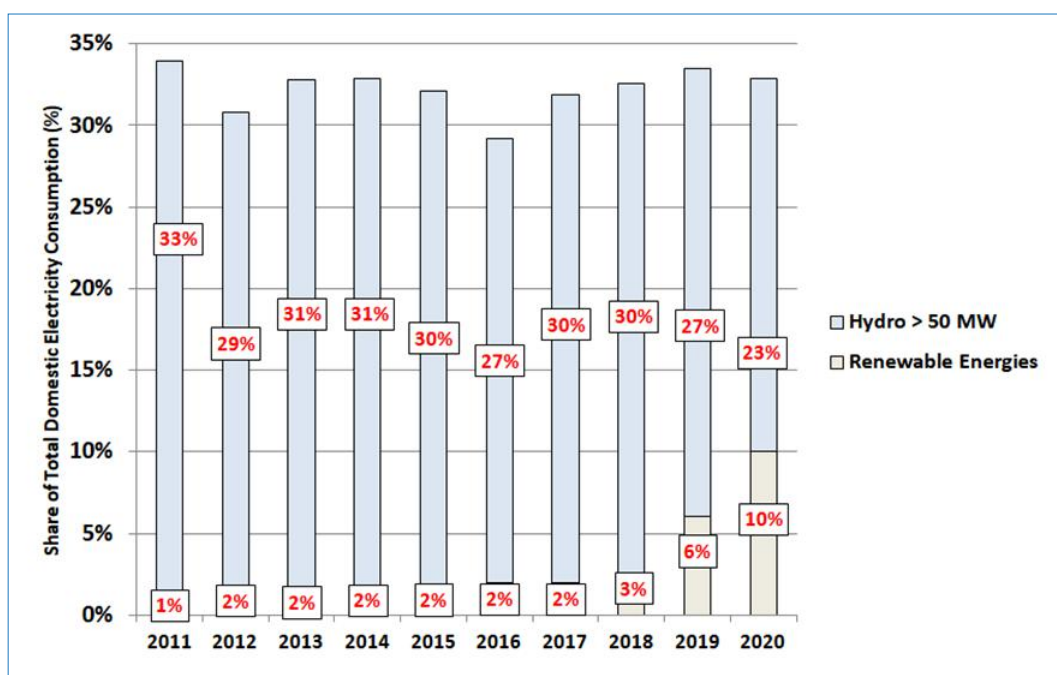


Fig. 4. Past performance

Source: CAMMESA (Argentine Wholesale Power Market Administrator)

<sup>1</sup> <https://www.argentina.gob.ar/normativa/nacional/resoluci%C3%B3n-447-2019-332234>

<sup>2</sup> <https://www.argentina.gob.ar/normativa/nacional/ley-27520-333515>

<sup>3</sup> [https://www.energia.gob.ar/contenidos/archivos/Reorganizacion/renovables/legislacion/ARGENTINA - Renewable\\_Energy\\_Law\\_Act\\_27191\\_\(English\\_version\).pdf](https://www.energia.gob.ar/contenidos/archivos/Reorganizacion/renovables/legislacion/ARGENTINA - Renewable_Energy_Law_Act_27191_(English_version).pdf)

CO<sub>2</sub> emissions from electricity production 2019

Total CO <sub>2</sub> Emissions from electricity production 2019	35.7 MtCO <sub>2</sub>
Total Emissions/Total Electricity Generation	0.267 metric tonnes of CO <sub>2</sub> /MWh
Total Emissions/Electricity Generated by Fossil Fuel Power Plants	0.446 metric tonnes of CO <sub>2</sub> /MWh

Source: CAMMESA (Argentine Wholesale Power Market Administrator)

## Energy balance (energy sources to end-uses)

SUPPLY AND CONSUMPTION	Mineral Coal	Crude Oil	Oil products	Natural gas	Nuclear	Hydro	Biofuels & Waste	Others	Total
Production	2.59	1,099.84		1,814.88		126.90	205.28	26.25	3,275.75
Imports	22.86		118.11	238.56	92.11	39.40			511.04
Exports	-1.51	-141.89	-200.21	-9.67		-0.92	-37.81		-392.01
Stock changes	6.70	15.62	9.38	-15.20					16.50
<b>TES</b>	<b>30.65</b>	<b>973.57</b>	<b>-72.72</b>	<b>2,028.58</b>	<b>92.11</b>	<b>165.38</b>	<b>167.47</b>	<b>26.25</b>	<b>3,411.28</b>
Transfers									
Statistical diff	-1.38	19.18	11.22						29.01
Electricity plants	-5.74		-41.28	-626.18	-92.11	-164.12	-32.41	519.96	-441.87
CHP plants									
Heat plants									
Blast furnaces	-16.83								-16.83
Gas works			113.76	-113.76					0.00
Coke ovens									
Oil refineries		-988.59	988.59						0.00
Petchem plants									
Liquefaction plants									
Other transf							-5.74		-5.74
Energy ind own use	-2.76	-4.14	-75.66	-214.82				-13.44	-310.83
Losses	-1.51		-73.86	-177.77		-1.26	-4.14	-75.11	-333.65
<b>TFC</b>	<b>2.43</b>	<b>0.01</b>	<b>850.05</b>	<b>896.05</b>	<b>0.00</b>	<b>0.00</b>	<b>125.19</b>	<b>457.66</b>	<b>2,331.38</b>
Industry	1.76		18.13	323.81			42.41	179.61	565.72
Transport			568.48	85.54			64.94	1.88	720.84
Other			209.09	405.37			17.84	276.16	908.45
Non-energy use	0.67		54.34	81.35					136.36
	<b>2.43</b>	<b>0.00</b>	<b>850.05</b>	<b>896.06</b>	<b>0.00</b>	<b>0.00</b>	<b>125.19</b>	<b>457.66</b>	<b>2,331.38</b>

Table 4. Argentina energy balance 2019 (expressed in PJ)

Source: National Energy Balance 2019 and own calculations (1 PJ = 0,27778 TWh)

### 3. Building sector

#### 3.1. Existing buildings

##### Energy balance 2019 (energy sources to end-uses)

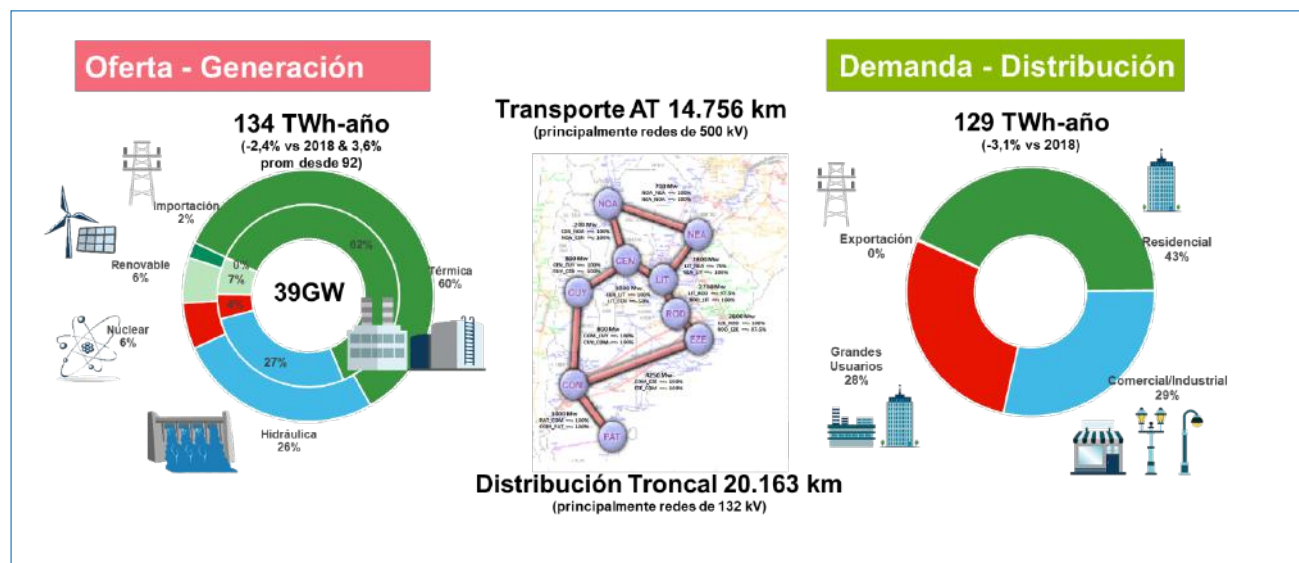


Fig. 5. Offer and Generation  
Source: [www.cammesa.com.ar](http://www.cammesa.com.ar)

##### Energy partition between single houses, apartment buildings and office buildings

	%
Single houses	14%
Apartment buildings	29%
Office buildings	18%
Rest of the activities	39%

Table 5. Energy partition between single houses, apartment buildings and office buildings

##### Which systems are mostly used for heating?

- Local systems (Furnaces, electric heating, heat pumps, solar thermal panels, geothermal systems, etc.)?

First, if available, natural gas stoves. Second, electric heating. Third, but on a much smaller scale, other sources like firewood, coal, etc.

- Heat networks (hot water, steam). In this case, which energy sources are used? What is the CO<sub>2</sub> content per MWh th?

In residential buildings of several stories, central heating is based on natural gas with radiant / heating slabs ( $\approx 0,42$  metric tonnes CO<sub>2</sub> per MWh). In office buildings or where natural gas is not available, central heating is based on electrical air conditioning ( $\approx 0,28$  metric tonnes CO<sub>2</sub> per MWh based on mix generation in Argentina).

##### Which systems are mostly used for cooling? (local systems, cooling networks)

If possible central cooling is based on electricity. Otherwise, independent electrical air conditioning will be used.

**What are the main choices of the national policy – if there is one – to reduce the emissions from the existing stock of buildings? To make this reduction affordable.**

- From a technological point of view? (Insulation, heat pumps, low CO<sub>2</sub> district network, geothermal systems, local PV production, etc.).
- From a regulatory point of view? Through land ownership regulations?
- Through subsidies, different financial mechanisms? Which are the priorities: reducing CO<sub>2</sub> or energy; Better inclusivity.
- Replacing parts of the existing stock of buildings?
- Is there a specific roadmap for this subject?

No national policy right now.

**Is there some roadmap for making existing cities more sustainable?**

No national policy right now.

**Are there some case studies or best practices you would like to share?**

No.

### 3.2. **New buildings**

**Does your country have a national policy regarding new buildings?**

**If yes, what are the priorities? (For housing and for office buildings)**

In study by the government. Not yet.

**Are some technologies prioritised, in particular for heating and cooling? At the building level? At the infrastructure level? (developing district networks, prohibiting connection to the gas network...)**

No.

**How are they supported? Through regulations? Subsidies?**

**Are there some recommendations and regulations for sustainable districts and cities?**

No

## 4. Industry

### 4.1. Cement Industry

#### What is the energy balance (energy sources used)?

#### And the GHG intensity, compared to other countries?

The first table in this presentation presents the sustainability indicators issued for 2019 by the Argentina Portland Cement Manufacturers Association (AFCP). The indicators were calculated according to GCCA-GNR.

CEMENT INDUSTRIE - SUSTAINABILITY INDICATORS		
GENERAL	unit	Year 2019
Total production volumes of clinker	Mt	8,15
Total production volumes of cement for estructural use	Mt	11,08
Total production volumes of cement for masonry use	Mt	0,84
Installed capacity	Mt	15,35
Number of plants		17
Number of cements certifies		70
Dispatch of cement in bags with respect total production (cement for structural use)	%	58,3
USED MATERIALS		
Traditional raw materials for clinker production	Mt / year	12,06
Alternative raw materials for clinker production	Mt / year	0,15
Traditional raw materials that added to clinker for cement production	Mt / year	2,55
Alternative raw materials that added to clinker for cement production	Mt / year	0,80
Materials used for packaging	kg/t cement	4,1
Clinker/Cement equiv. (GNR protocol, ref 092a)	%	70,2
ENERGY CONSUMPTION		
Direct energy consumption for clinker production (GNR protocol, ref 093)	GJ/t clinker	3,55
Direct energy consumption for clinker production (GNR protocol, ref 062)	GJ/t cement	2,49
% Consumption based on alternative fuels (without biomass)	%	3,1
% Consumption based on biomass	%	3,5
CO2 emission factor for kiln fuel mix (GNR protocol, ref 096) *	kg CO2/GJ	62,7
CO2 emission factor for kiln fuel mix (GNR protocol, ref 096). Decrease compared to 2015	kg CO2/GJ	3,40
Indirect energy consumption	GJ/t cement	0,35
% Consumption based on renewable sources	%	36,60
<b>Total energy consumption</b>	GJ/t cement	2,84
EMISSIONS TO THE ATMOSPHERE		
CO <sub>2</sub> Emission		
Specific Gross CO <sub>2</sub> of cementitious product (GNR protocol, ref 062)	kg CO2/t cement	519
Specific Indirect CO <sub>2</sub> from external power generation (GNR protocol, ref 082a)	kg CO2/t cement	28
Total gross CO2 emissions, excluding CO2 from on-site power generation **.	kg CO2/t cement	547
Total gross CO2 emissions, excluding CO2 from on-site power generation. Decrease	%	5,40
Other Emissions		
NO <sub>3</sub>	kg/t cement	2,22
SO <sub>3</sub>	g/t cement	22
Particulate matter ***	g/t cement	72
WASTE		
Hazardous waste generated	kg/t cement	0,06
% Reused, recycled or recovered	%	69,3
Non-hazardous waste generated	kg/t cement	0,49
% Reused, recycled or recovered	%	50,4
REFERENCE INDICATORS		
In 2015 the reference indicators were,		
* CO2 intensity factor of the fuel mix: 66.1 kg CO2 / GJ		
** Total gross CO2 emissions, excluding CO2 from on-site power generation: 578 kg CO2/t cement		
*** Particulate matter: 128 g/t cement		

Table 6. Cement industry – Sustainable indicators

Table 7 shows the energy balance (energy sources used) according to the above-mentioned restricted information delivered to the ANI by AFCP.

Description	% of thermal energy demand		
	2019	2030	2050
Reference year			
Coal	0.2	0.0	0.0
Petcoke	22.4	25.0	0.0
Natural gas	70.5	60.0	65.0
Waste of fossil origin (including fossil fuel from mixed fuels)	3.1	8.0	20.0
Biomass (including biomass from mixed fuels)	3.5	7.0	15.0
Other remaining fuels	0.0	0.0	0.0
Sum of fuels composition shares	100.0	100.0	100.0

Table 7. Energy Balance

## Are the best available low carbon technologies used / considered?

### If not, is it an economic problem? A matter of regulation? Or some social issues?

The AFCP conducted a study of 21 measures selected from the 52 technologies developed in WBCSD<sup>4</sup> -CSI<sup>5</sup> / ECRA<sup>6</sup> Technology Papers 2017.

Regarding its implementation, the following issues were investigated: a) the current degree of progress; b) if there is potential in the 2018-2030 period; and c) the limitations for local applications. The investigation was strictly technical and did not include financial-economic feasibility.

The technologies for the reduction of the clinker content (strategies # 31, 34, 35, 36 and 37 of CSI/ECRA) and of the carbon footprint in the fuel matrix (strategies # 13 and 14 of CSI/ECRA) were evaluated.

The technologies for capturing, storing and reusing CO<sub>2</sub> (# 43 to 52 inclusive) were not taken into account, considering that there is no certainty of their viability at the 2030 horizon.

The other CSI/ECRA technologies were discarded as locally unviable or still in the development stage.

## Is there a roadmap to decrease GHG emissions for 2030 - 2050

### If yes, what are the intermediary steps?

Table 8 shows the vision of the Argentine cement industry regarding GHG emissions towards the years 2030 and 2050. To date, there are no estimates for intermediate stages.

<sup>4</sup> World Business Council for Sustainable Development

<sup>5</sup> Cement Sustainability Initiative

<sup>6</sup> European Cement Research Academy

GHG EMISSIONS - VISION CEMENT INDUSTRY ARGENTINA					
Description	Note	Unit	2019	2030	2050
<b>Clinker process emissions</b>					
Calcination process emissions factor	(i)	kg CO <sub>2</sub> /kg clinker	0,536	0,536	0,536
CO <sub>2</sub> from organic carbon in limestone (TOC)	(ii)	kg CO <sub>2</sub> /kg clinker	0,011	0,011	0,011
Alternative de-carbonated raw-materials for clinker production. Possible application	(iii)			x	
Total clinker CO <sub>2</sub> emission factor (direct emissions)	(iv)	kg CO <sub>2</sub> /kg clinker	0,77	0,76	0,72
<b>New binders</b>					
Share of new binders in concrete production	(v)	%	0,00	0,00	3,00
New binders average CO <sub>2</sub> emissions factor	(vi)	kg CO <sub>2</sub> /kg binder	0,00	0,00	0,30
<b>Cement</b>					
Cement production (excluding SCM for use in concrete plants)	(vii)	Mt cement	11,9	13,6	15,1
Clinker factor	(viii)	kg CO <sub>2</sub> /kg clinker	0,70	0,68	0,60
Specific CO <sub>2</sub> emissions in Cement & Binder, including change in SCMs for use in concrete	(ix)	kg CO <sub>2</sub> /kg cementitious	0,547	0,537	Net carbon neutrality in concrete stage

Table 8. GHG Emissions – Vision cement industry Argentina

- (i) Indicates the CO<sub>2</sub> emission in clinker production associated only with calcination.
- (iii) It is expected to apply this technology by 2030.
- (iv) It is the total emission to produce clinker. Includes calcination (i) and use of fuel. It excludes that associated with the production of electrical energy and the use of biomass.
- (v) The new binders to implement are not specified. The category includes cements manufactured based on belite clinker, aluminous cements, alkaline activated binders, magnesian cements, among the most renowned.
- (vi) The emission factor indicated is an international average reference value.
- (ix) It is the CO<sub>2</sub> emission per tonne of cementitious material, which in Argentina today is equivalent to cement. It includes the partial neutralisation of the carbon footprint by re-carbonation of concrete, mortar and cement-based pastes. A CO<sub>2</sub> capture factor equivalent to 20% of the emission due to calcination in clinker production (average reference value of the GCCA) was estimated.

## Is the implementation of low-carbon technologies helped by the government?

### For refurbishing or replacing equipment?

It is not foreseen.

### How are public authorities pushing the transformation?

#### Through benchmarking?

In 2014, Argentina emitted a total of GHG equal to 368 MtCO<sub>2e</sub>. Of these, 11.1% (40.9 Mt) corresponded to the industrial sector.

In Argentina, the cement industry produces 1.5-2.0% of total GHG emissions. As a reference, on the worldwide level, it is 7-8%.

To mitigate these emissions in the cement industry, two measures were established:

- a) Reduction of the clinker factor in cement. Unconditional goal by 2030: to 70%. In Argentina, it implies a reduction of 0.368 MtCO<sub>2</sub>. This goal (70% clinker factor) was already obtained in 2019.
- b) Co-processing - Thermal substitution in clinker furnaces (use of alternative fuels):
  - Unconditional goal to 2030: 5%

- Conditional goal to 2030: 15% (Its fulfilment is subject to legal, technical and economic / financial conditions).

#### Audits?

No audits are foreseen. Only its possible instrumentation is considered.

#### Other incentives. Fuel taxes

At the moment, there is only one regulation regarding CO<sub>2</sub> taxation on fuels in the country, which applies to some fuels used by the industry (petroleum coke and other liquid fossil fuels). The CO<sub>2</sub> tax on fuels today amounts to about USD 5 per tonne of coke.

#### Are there incentives for carbon capture, utilisation, and storage? How?

There are no incentives.

#### If relevant, what about recycling? What percentage is recycled? What are the obstacles to increase recycling? Is a policy to increase recycling already in place or in project?

Tables 1 and 2 include indicators on the use of alternative fuels, raw materials and waste recycling.

Currently there is only one regulation regarding CO<sub>2</sub> taxation on fuels in the country, which affects some fuels used by the industry (petroleum coke and other liquid fossil fuels). The CO<sub>2</sub> tax on fuels today amounts to about USD 5 per tonne of coke.

Nowadays, recycling is not relevant in the concrete industry. However, there are some actions in that direction.

#### Are there some case studies or best practices you would like to share?

We can highlight the following cases and / or practices.

- Low CO<sub>2</sub> intensity in the fuel mix in the clinker furnace, even despite a thermal substitution rate lower than the world average. This is a consequence of the high rate of natural gas use.
- Low intensity of CO<sub>2</sub> per tonne of cement, due to the previous point a) and the low clinker factor.
- Use of calcined clays as artificial pozzolana. This is an industrial-commercial practice since 2018 (Cementos Avellaneda). The conditions for implementing this process were studied for factories located far from supply sources of other Supplementary Cementing Materials (SCM). The use of calcined clays as artificial pozzolana made it possible to reduce the Clinker factor.

## 4.2. Chemical Industry

#### What is the energy balance (energy sources used)?

#### And the GHG intensity, compared to other countries?

There is no published energy or emissions data for industry — only a government estimate (2016) of total chemical industry emissions of 2,5 MtCO<sub>2e</sub>, or 6,1% from the total industry sector. The National petrochemical Institute, IPA, will work with local industries to develop data on energy use / decarbonisation plans and GHG intensity. This will start in October.

The Chemical and Petrochemical Manufacturing Association does not have any information on GHG. Some data obtained directly from industry are shown below (Emissions units: metric tonnes of CO<sub>2e</sub>):

Process emissions	
Ethylene	0.4 tonnes/tonne ethylene
Polyethylene	0.16/tonnes pe
Polypropylene	0.3 tonnes/tonne pp
Total emissions, process plus fuel value	
PET	1.35/tonne PET
Polypropylene	1.343/ tonne PP
PVC	1.65 tonnes/tonne PVC

Table 9. Process emissions

**Are the best available low carbon technologies used / considered?****If not, is it an economic problem? A matter of regulation? Or some social issues?**

There are local initiatives, such as using heat pumps for reboilers in distillation. There are no regulations or incentives. By 2025, 20% of electricity consumption in all industries will be covered by renewable energy.

**Is there a roadmap to decrease GHG emissions for 2030 - 2050****If yes, what are the intermediary steps?**

No roadmap established for 2030 / 2050.

**Is the implementation of low-carbon technologies helped by the government?****For refurbishing or replacing equipment? How are public authorities pushing the transformation? Through benchmarking? Audits?**

No government support or audits.

**Are there incentives for carbon capture, utilisation, and storage? How?**

No government support or audits.

**If relevant, what about recycling? What percentage is recycled? What are the obstacles to increase recycling? Is a policy to increase recycling already in place or in project?**

Recycling of plastics is around 15%. A law being is prepared to incentivise recycling.

**Are there some case studies or best practices you would like to share?**

A private energy efficiency audit recommended the installation of gas turbines for power generation and heat recovery to petrochemical installations. The chemical / petrochemical production of Argentina for 2020 is shown below.

Argentina chemical / petrochemical Production 2020-IPA statistics- (tonnes/yr)	
Ammonia	778 003
Urea	1 283 575
Ethylene	736 784
Polyethylene	644 277
Polypropylene	201 800
PVC	162 628
Polystyrene	63 597
Methanol	223 521
PET	160 000
Caustic soda	269 937
Chlorine	232 816
Benzene	89 664
Toluene	78 014

**Table 10.** Argentina Chemical / Petrochemical  
Production 2020-IPA statistics- (tonnes/yr)

Table of Contents

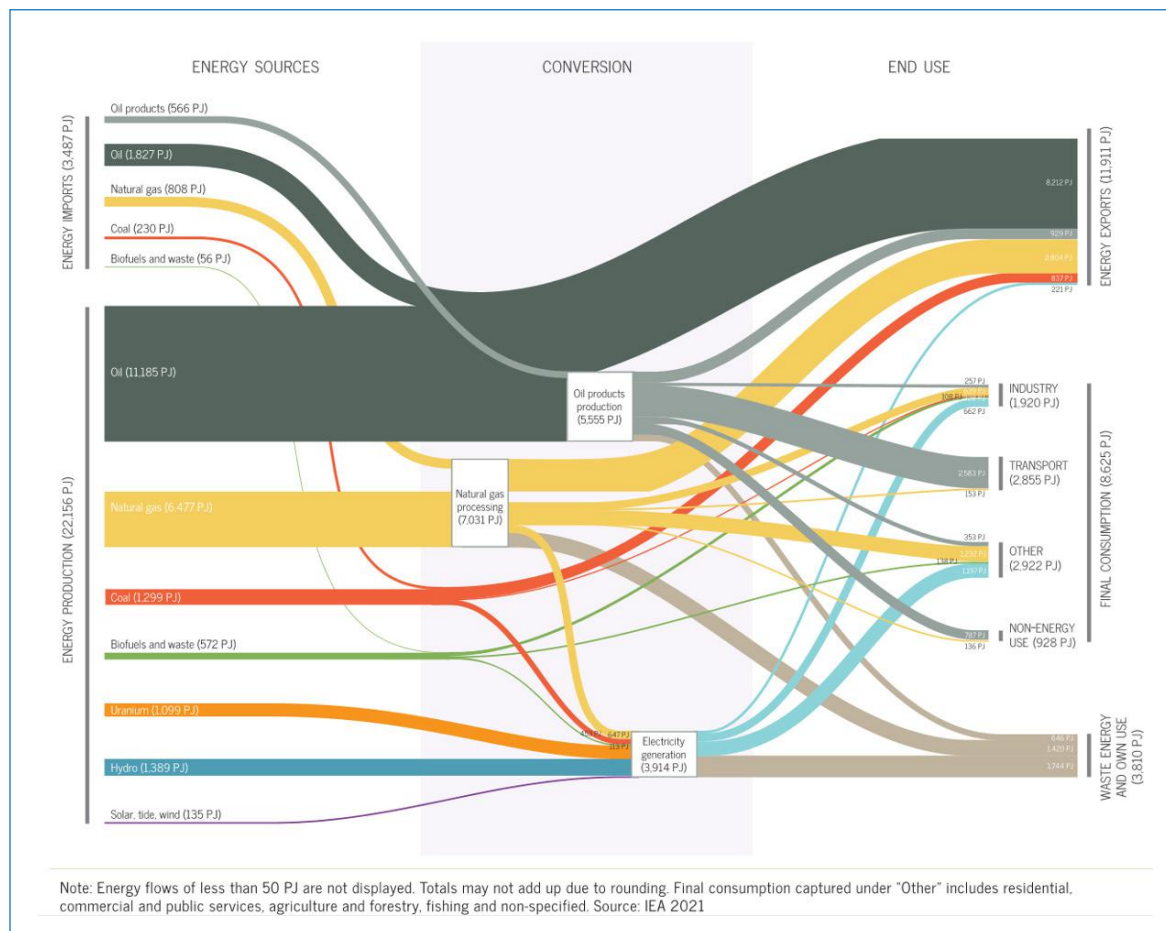
Canada ..... 300

## Canada

### What is the energy balance (energy sources used)?

### And the GHG intensity, compared to other countries?

The diagram below shows the energy flows in the Canadian economy.



**Fig. 1.** Sankey diagram of the energy flows in the Canadian economy. Source: IEA 2021

As highlighted in the 2021 edition of the Canadian Energy Outlook, the Canadian energy system displays several characteristics that make it stand out from other countries. The abundance of domestic resources allowing Canada to be a major energy exporter explains not only the size and composition of its energy sector but also how and where energy is used across the country. However, presenting the energy system at the national scale hides the fact that the production and use of energy vary greatly across provinces. If similarities across provinces can be observed mainly on the consumption side in sectors like transport or commercial and residential buildings, it is the opposite for the industrial sector, whose importance in energy consumption varies greatly on a provincial basis, a difference attributable mostly to energy production activities.

## Canada Total Primary Energy Supply

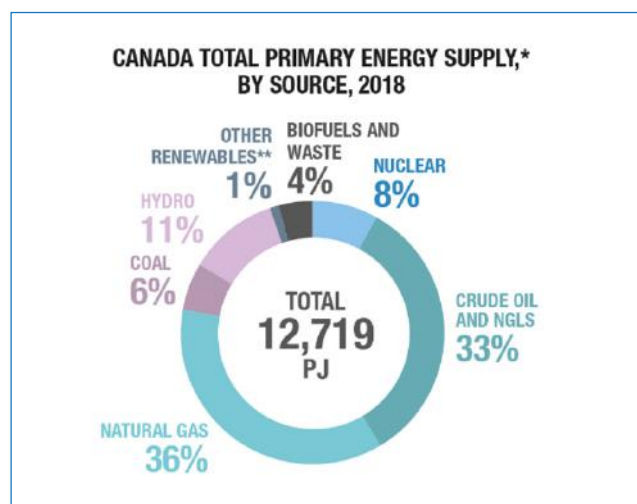


Fig. 2. Canada's Total Primary Energy supply -Canada Energy Factbook 2021

Canada's total primary energy **supply** for the domestic market in 2018 was 12 719 petajoules (3 533 TWh). Natural gas accounted for 36% of the total primary energy supply, followed by crude oil and NGLs at 33%, hydro at 11%, nuclear at 8%, coal at 6%, and other renewables at 1%.

According to Statistics Canada (2021), the primary energy **production** in Canada was 21 414 petajoules (5 948 TWh) in 2019. Crude oil accounted for the largest proportion of primary energy production in Canada at 50.1%, followed by natural gas (31.8%), primary electricity (8.5%), coal (5.3%) and gas plant natural gas liquids (4.3%). Crude oil accounted for the largest share of primary energy production for the tenth consecutive year.

Exports of Canadian energy and energy products were 13 904 petajoules (3 862 TWh). In 2019, Canada exported 80.6% of its crude oil production and 42.9% of its marketable natural gas. Imports of energy were 4 097 petajoules (1 138 TWh). Crude oil accounted for 43.8% of imports, followed by natural gas (30.2%).

Domestic energy consumption was 8 882 petajoules (2 467 TWh).

The oil and gas sector is responsible for a significant amount of GHG emissions as shown in the figure below.

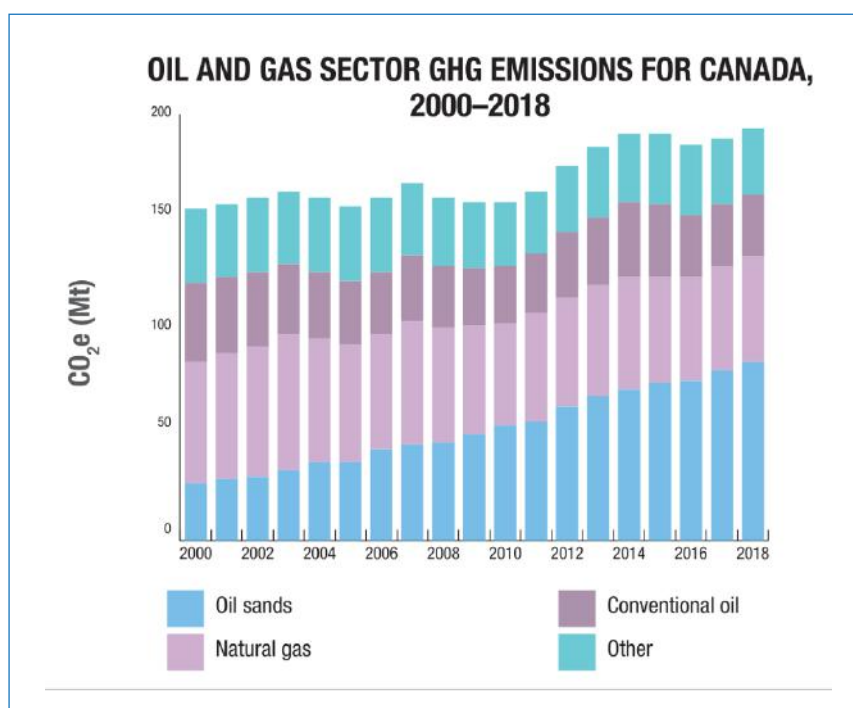


Fig. 3. GHG emissions from the Oil & Gas sector. Source: Canada Energy Factbook 2021

GHG emissions from oil and gas production have gone up 23% between 2000 and 2018, largely from increased oil sands production, particularly in situ extraction which requires a lot of steam. During this period, oil sands production emissions more than tripled while conventional oil and natural gas emissions decreased by 14%. If nothing is done, the overall emissions should increase to 194 Mt by 2030.

### Is the implementation of low-carbon technologies helped by the government?

#### What legal status do the related documents have? What is their timeline?

Canada's various levels of government (federal, provincial and territorial, and municipal) have plans to cut GHG emissions and accelerate the energy transition in order to fulfil Canada's commitment to the 2015 Paris Agreement. Objectives have been set for 2030 and 2050 but there is no official roadmap to achieve the objectives. Several projections and scenarios have been studied to establish decarbonisation pathways, which are used below to address the topics raised in the questionnaire.

To facilitate the reading, here is the conversion factor:

$$1 \text{ PJ} = 0.277 \text{ TWh} = 163 \text{ 450 boe}$$

### Is there a roadmap to decrease GHG emissions for 2030 - 2050

#### If yes, what are the intermediary steps?

The Canadian strategy to decrease the country's carbon footprint is not focusing only on oil and gas as shown below.

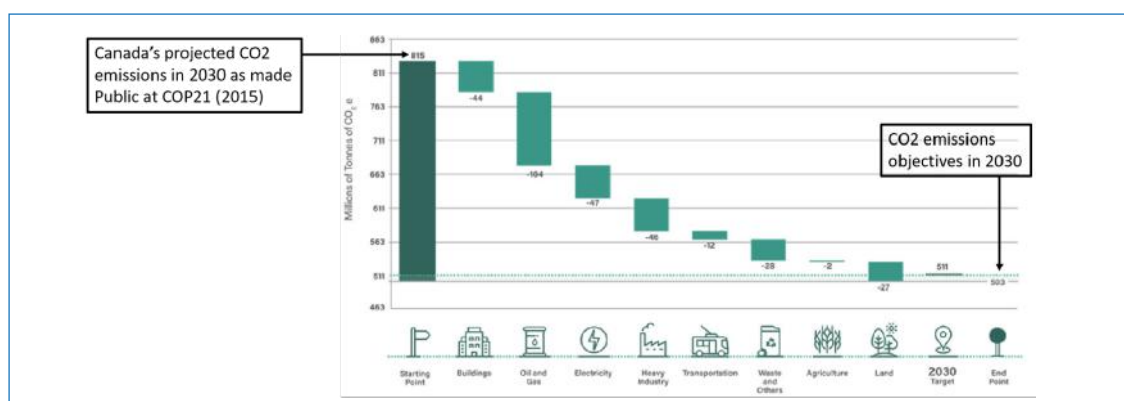


Fig. 4. Projected reduction in CO<sub>2</sub> emissions in 2030 by sector.

In order to achieve the objectives, several measures are envisaged.

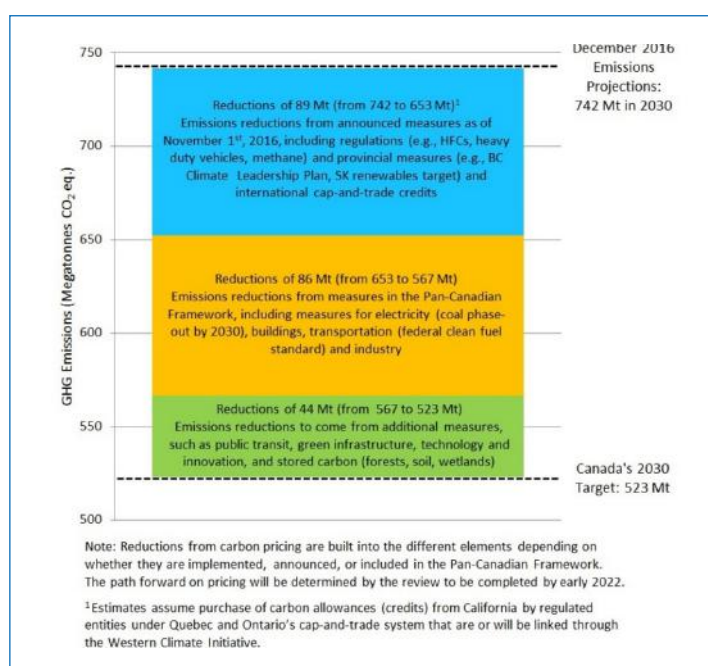


Fig. 5. Pathway to meeting the GHG reduction target by 2030

This bar graph shows the pathway to meeting Canada's target for greenhouse gas emission reductions by the year 2030. The top of the bar reflects Canada's December 2016 greenhouse gas emissions projections for the year 2030 which is estimated to be 742 Mt of carbon dioxide equivalent greenhouse gases, while the bottom of the bar shows Canada's 2030 target of 30% below 2005 levels, which is equal to 523 Mt. Note that reductions from carbon pricing are built into the following sections of the bar graph depending whether they are implemented, announced, or included in the Pan-Canadian Framework.

The top section of the bar reflects emissions reductions from measures announced as of November 1, 2016, including regulations for heavy-duty vehicles, hydrofluorocarbons, and methane for the oil and gas sector. Provincial climate change measures are also reflected in this section, including British Columbia's Climate Leadership Plan, and Saskatchewan's plans to increase renewables for electricity generation. This is projected to bring Canada's 2030 greenhouse gas emissions to 653 Mt of carbon dioxide equivalent greenhouse gases, down 89 Mt from the December 2016 emissions projections. This bar also assumes purchases of carbon credits from California by regulated entities under Quebec's cap-and-trade system that is or will be linked through the Western Climate Initiative.

The middle section of the bar reflects measures presented in the Pan-Canadian Framework on Clean Growth and Climate Change including for: electricity, including phasing out coal-traditional coal-fired electricity by 2030; buildings; transportation, including the clean fuel standard; and industry. This is projected to bring Canada's 2030 greenhouse gas emissions to 567 Mt of carbon dioxide equivalent greenhouse gases, down an additional 86 Mt from the measures announced as of November 1, 2016.

The bottom section of the bar reflects reductions to come from additional measures, such as public transit, green infrastructure, innovation, and stored carbon in forests, soil, and wetlands. This is projected to bring Canada's 2030 greenhouse gas emissions to 523 Mt of carbon dioxide equivalent greenhouse gases, down an additional 44 Mt from the measures announced as of November 1, 2016, and as found in the Pan-Canadian Framework on Clean Growth and Climate Change. This bottom section meets Canada's target of 30% below 2005 levels by 2030.

Late June 2021, Bill C-12 have been voted in Parliament. While imperfect, it will require the Canadian government to set and regularly report on progress meeting national targets for reducing greenhouse gas emissions. In setting targets, the government must take into account the best available science and Indigenous knowledge, as well as input from an already established independent expert advisory body. The bill also requires the federal environment commissioner to report on the government's progress at least once every five years.

Several trajectory scenarios have also been proposed to achieve a net-zero economy

(Canadian Energy Outlook 2021) – specifically:

- CP30: policies in place in 2020 + carbon tax @170 CAD/t in 2030
- NZ60: -30% by 2030, -80-% by 2050, net-zero in 2060
- NZ50: -40% by 2030, net-zero in 2050 (current federal government ambitions)

	2016	2030			2050		
	MtCO <sub>2e</sub>	CP30	NZ60	NZ50	CP30	NZ60	NZ50
Reductions wrt 2005 (730 MtCO <sub>2e</sub> )		-9%	-28%	-38%	-15%	-79%	-100%
Total emissions (MtCO <sub>2e</sub> )	705	642	511	438	598	146	0
<b>Main contributing sectors</b>							
Electricity	82	-60%	-70%	-89%	-94%	-155%	-167%
Waste	17	-52%	-63%	-63%	-58%	-64%	-68%
Oil and gas (including fugitive emissions)	161	+7%	-54%	-60.0%	+14%	-88%	-94%

**Table 1.** Reduction of CO<sub>2</sub> emissions according to scenarios for 2030 and 2050

## Roadmap for the energy mix

The evolution of the Canadian energy mix (primary energy use) is shown below along with two scenarios for the future: 'Reference' (-●-●-●-) corresponds to the policies announced as of Sept. 2020 and 'Evolving' (coloured areas) to enhanced policies with stronger federal government ambitions.

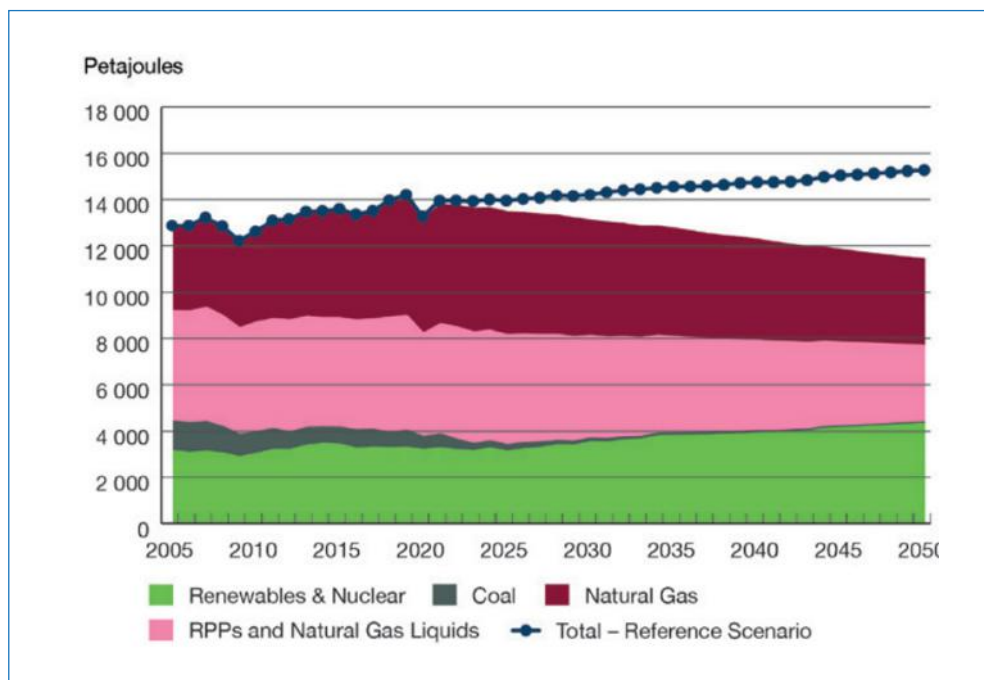


Fig. 6. Roadmap for the energy mix 2005 to 2050 by fuel type. Source: Canada Energy Future (2020)

In the Evolving Scenario, the consumption of fossil fuels in Canada remains below its 2019 peak. By 2030 it is 12% lower, and 35% lower by 2050. Coal declines in the 2020s as it is phased out of electric generation. Refined petroleum product (RPP) use gradually declines due to energy efficiency improvements and increased use of renewable fuels and electricity. Natural gas use increases in the early part of the projection, driven by increasing demands in electricity generation, and upstream crude oil and natural gas production. Natural gas use falls in the latter parts of the projection, as renewables play a bigger role in electricity generation, leading to decreasing needs of fossil fuels in this sector. In contrast, fossil fuel consumption is relatively unchanged throughout the projection period in the Reference Scenario. This is due to steady improvements in energy efficiency offsetting population growth and increasing industrial output, particularly in the oil sands, as well as a shift to the service economy. At the same time, demand for renewable energy sources such as hydroelectricity, wind, solar, and biofuels increases by 45% from 2019 to 2050 in the Evolving Scenario. Nuclear demand increases by 2%. Combined with declining fossil fuel use, the share of these low and non-emitting sources increases from 23% of the energy mix in 2019, to 38% by 2050. To meet these rising demands, Canada relies more on renewable generation. Wind, solar, and hydro electricity generation grow in the projections. In the Evolving Scenario, 90% of electricity generation comes from renewable and nuclear generation in 2050. This compares to 81% today.

## Roadmap for the GHG emissions

Sectoral and economy-wide measures are expected to reduce Canada's emissions by 144 Mt by 2030, relative to 674 Mt of greenhouse gas emissions in 2030 under the 2020 Reference Case. The LULUCF accounting contribution, plus the expected impact of the proposed nature-based solutions and the measures in the plan to reduce emissions from fertilizer use in agriculture combined are expected to reduce emissions by a further 27 Mt. Combined, these reductions arrive at approximately 503 Mt in 2030, or about 8 Mt below Canada's 2030 target. This represents about a 31% reduction below Canada's 2005 emissions.

The Table below illustrates the expected emission reductions of the measures included in the plan in 2030.

	Projected Emissions in 2030 (MT)
<b>2020 Reference Case</b>	<b>674</b>
<b>Sectoral Measures, post-2022 carbon price and CFS (liquid only)</b>	<b>144</b>
<b>LULUCF accounting contribution</b>	<b>17</b>
<b>Nature-Based Solutions and agriculture measures</b>	<b>10</b>
<b>Total Projected Emissions from the Plan</b>	<b>503</b>
<b>Canada's 2030 Target</b>	<b>511</b>

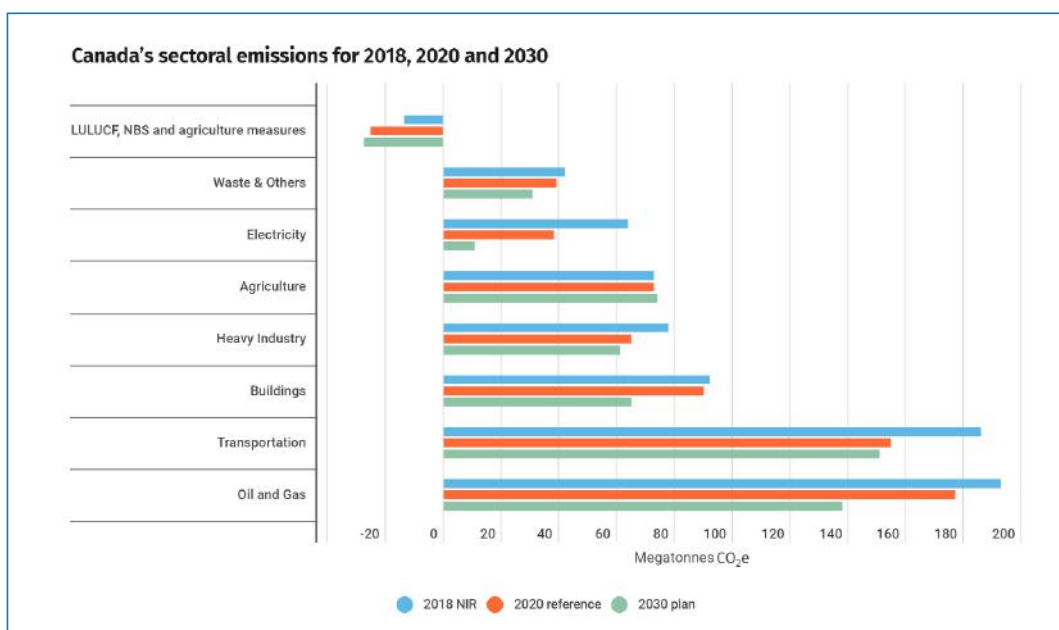
*Table 2.* Expected emission reductions from the measures included in the Evolving Scenario in 2030

The following Table shows emission reductions by sector from 2005 levels.

	Historical				Projected		Change 2005 to 2030
	2005	2010	2015	2018	2020	2030	
Oil and Gas	158	159	191	193	177	138	-20
Electricity	119	96	81	64	38	11	-108
Transportation	161	168	172	186	155	151	-10
Heavy Industry	87	75	79	78	65	61	-26
Buildings	86	82	86	92	90	65	-21
Agriculture	72	68	71	73	73	74	2
Waste & Others	46	42	41	42	39	31	-15
LULUCF, NBS and agriculture measures	n.a.	11	-8	-13	-25	-27	-27
<b>Total (incl. LULUCF)</b>	<b>730</b>	<b>702</b>	<b>712</b>	<b>716</b>	<b>612</b>	<b>503</b>	<b>-227</b>

*Table 3.* Emission reductions by sector from 2005 levels

The Figure below shows the evolution of Canada's targets in the last 3 year. The 2018 data comes from the National Inventory Report (NIR).



*Fig. 7.* Emission targets in 2018 and 2020 and projected target for 2030 (according to the plan)

Source: [https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climate-plan/healthy\\_environment\\_healthy\\_economy\\_plan.pdf](https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climate-plan/healthy_environment_healthy_economy_plan.pdf)

In order to achieve the above targets, some milestones have been proposed as shown below.

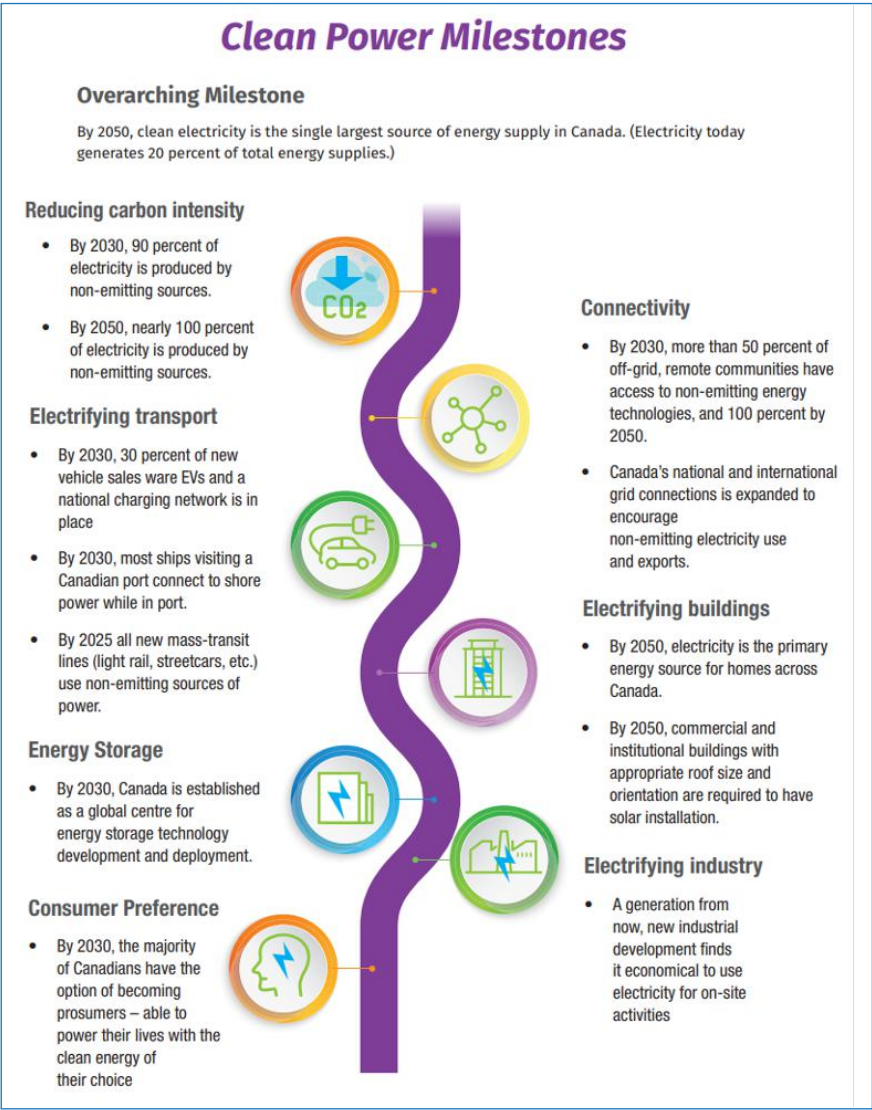


Fig. 8. Canada’s Energy Transition (2018)

Canada has one of the highest GHG intensities per capita as evidenced in the bar chart below. Several factors can explain such a high emission level namely the size of the country (transport of goods and people over large distances), the climate conditions (hot summer and cold winter), and the industrial structure where the extraction of raw materials plays an important role.

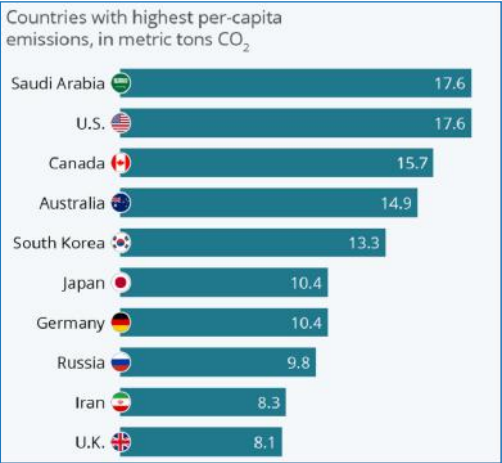
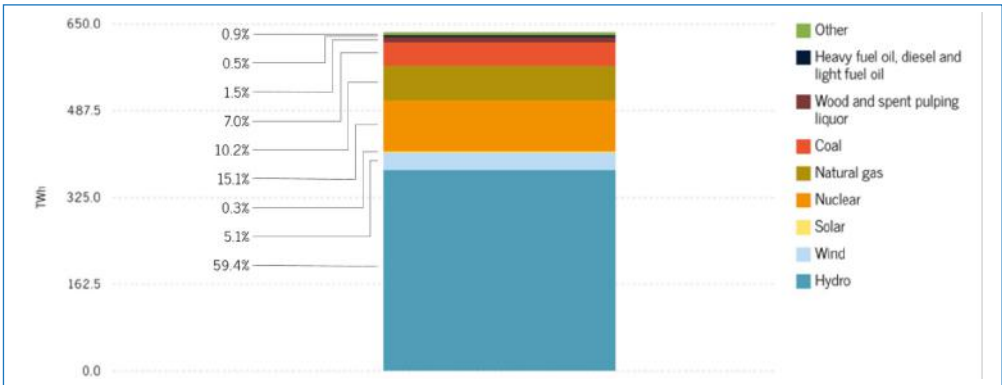


Fig. 9. GHG intensities per capita in the 10 top countries. Source: Statista (2021)

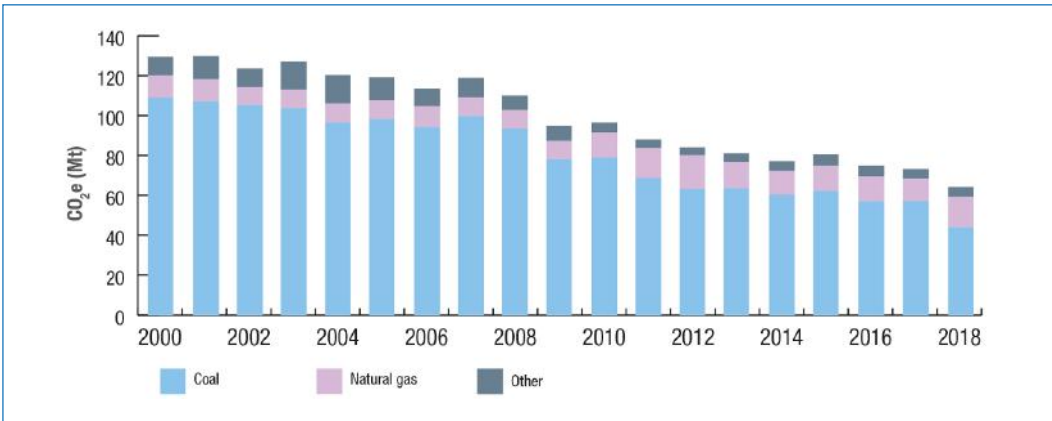
### Roadmap for the electricity mix and CO<sub>2</sub> emissions

The electricity mix in Canada is already significantly decarbonized as shown below.



**Fig. 10.** Canadian electricity mix. Source: Statistics Canada 2021

The evolution of the electricity sector’s GHG emissions until 2018 is shown below.



**Fig. 11.** Historic reduction of GHG emissions from electricity generation from 2000 to 2018 Source: Natural Resources Canada 2021

Greenhouse gas emissions (GHG) from electricity generation were stable at almost 130 MT in 2001. Since then, GHG emissions have declined to less than 70 MT in 2018. Renewable electricity generation has increased by 16% between 2010 and 2018, with solar and wind having the largest growth. In 2018, almost 82% of electricity in Canada came from non-GHG-emitting sources. Hydro made up 60%, nuclear 15%, and other renewables the remaining 7%.

With the projected shutdown of coal extraction in the coming years and the repowering of power plants, the carbon footprint of the electricity mix will further improve. Power generation is expected to continue to grow due to the further electrification of the economy (transportation and buildings) as well as for demographic reasons. The projected evolution of the electricity mix until 2050 is shown below. It should be noted that wind energy will play a major role. Indeed, many regions have favourable wind conditions (onshore and offshore) and the deployment of wind parks is relatively quick as compared to the construction of new hydro-dams or nuclear plants.

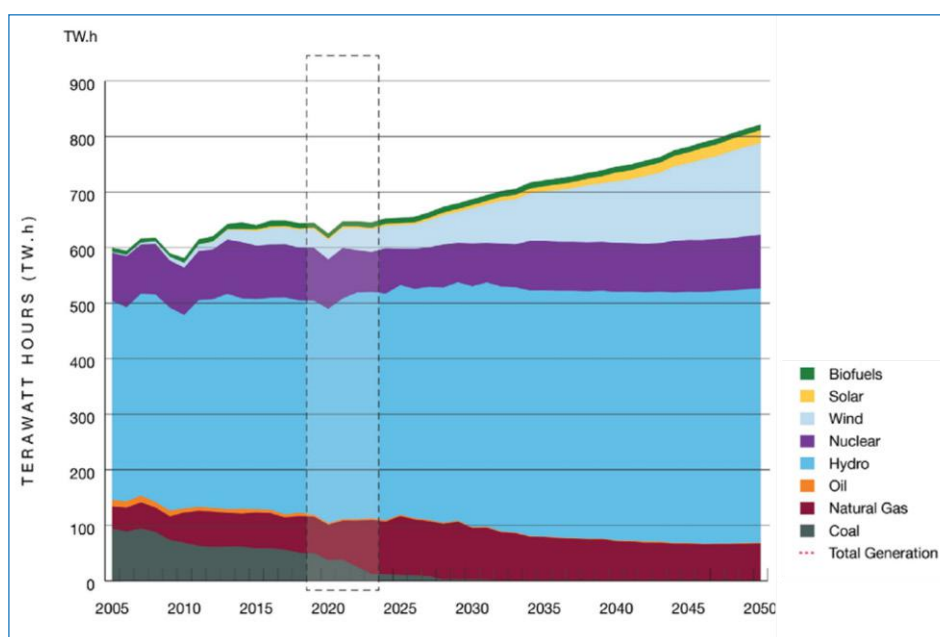


Fig. 12. Historic and projected electricity generation by type of energy source. Source: Canada's Energy Future 2020

### Carbon capture, utilisation, and storage in Canada

Canada is a leader in carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) with a number of operating projects and decades of experience in the technology (about 17 per cent of global CCUS projects in operation or under construction). CCS separates (or “captures”) CO<sub>2</sub> from industrial exhaust, for example, at coal power plants, before injecting it into deep underground rock formations. CCUS “utilises” CO<sub>2</sub> for other things, including enhanced oil recovery (EOR), which is a process of injecting CO<sub>2</sub> into declining oil fields to help to recover additional oil from reservoirs.

Western Canadian CCS projects are possible because of a combination of technical expertise, geological suitability for CO<sub>2</sub> storage, and legal, regulatory, and policy frameworks. The number of operating projects continues to grow. In 2014, the SaskPower Boundary Dam power station became the world's first power plant with CCS. In 2015, the largest CCS project in Canada, Shell's Quest CSS project began capturing CO<sub>2</sub> from a bitumen upgrader near Edmonton and injecting it into an underground reservoir for storage. The Alberta Carbon Trunk Line (ACTL) is on-stream since the first half of 2020. ACTL takes CO<sub>2</sub> from the new Sturgeon refinery and a nearby fertiliser plant and transports it by pipe 240 kilometres to an EOR project in central Alberta. The Quest and ACTL projects, at 1.0 and 1.7 million tonnes of CO<sub>2</sub> per year respectively, store the equivalent emissions of 600 000 cars annually. The CO<sub>2</sub> is pumped into the oil-bearing rock formation to recover more oil. The additional recovery potential is 15-20% of the original oil

The table below summarizes the present projects.

Facility name (click on link to view)	CO <sub>2</sub> capture capacity (Mtpa)	Primary storage type
Alberta Carbon Trunk Line ("ACTL") with North West Sturgeon Refinery CO <sub>2</sub>	1.2-1.4	Enhanced oil recovery
Alberta Carbon Trunk Line ("ACTL") with Nutrien CO <sub>2</sub> Stream	0.3-0.6	Enhanced oil recovery
Boundary Dam Carbon Capture and Storage	1.0	Enhanced oil recovery
Great Plains Synfuel Plant and Weyburn-Midale	3.0	Enhanced oil recovery
Husky Energy Lashburn and Tangleflats CO <sub>2</sub> Injection in Heavy Oil Reservoirs	0.2	Enhanced oil recovery
Inventys and Husky Energy VeloxoTherm Capture Process Test	0.1	Enhanced oil recovery
Quest	1.0	Dedicated geological storage - onshore deep saline

Table 4. Current CCS projects. Source: Canada Energy Regulator 2021

As highlighted by the Oxford Institute for Energy Studies (2021), future growth of CCUS in Canada is expected to be spurred by increased deployment of capture technologies in mature industries such as oilsands extraction, refining, and fertilizer and cement manufacturing. For instance, the ACTL is fed by both the oilsands-based NWR Sturgeon refinery and the Nutrien fertilizer plant. Growth is also expected from DACCS and BECCS, with Canadian firm Carbon Engineering considered a pioneer of the former. Until recently, the deep decarbonization of these industries in the near to medium term was viewed as a longshot.

Several projects have recently been announced for the production of hydrogen from decarbonized natural gas, and the transport of CO<sub>2</sub> for sequestration, alongside promises of future green hydrogen projects.

### Blue Hydrogen

Project	Partners	Location	Carbon capture	Start date
Blue hydrogen plant	Air Products, Alberta and Canadian governments	Edmonton, AB	3 Mt/year	2024
Polaris Phase 1 (blue hydrogen)	Shell Canada	Fort Saskatchewan, AB	0.75Mt/year	2025
Blue hydrogen plant	Suncor and ATCO	Edmonton, AB	2 Mt/year	2028

**Table 5.** Blue hydrogen project

### CO<sub>2</sub> Pipelines

Project	Partners	Hub	Capacity	Start Date
Alberta Carbon Grid	TC Energy and Pembina Pipeline	Fort Saskatchewan, AB	20 Mt/year	2025
CO2 Trunkline	Cenovus, CNRL, Imperial, MEG and Suncor	Cold Lake, AB	40 Mt/year	TBA

**Table 6.** Proposed CO<sub>2</sub> pipelines

The most important of these announcements was the alliance of the five largest oilsands-based energy firms to form the Oilsands Pathways to Net Zero Initiative 30. Together, these firms – Cenovus, CNRL, Imperial, MEG Energy, and Suncor – control over 90 per cent of Canada’s oilsands production. While they have previously demonstrated a willingness to collaborate, as seen in the technology-driven Canada’s Oilsands Innovation Alliance (COSIA), this would mark the first time that they all partner to deliver major projects of this size and scale. If all the announced blue hydrogen projects are sanctioned, Canada’s CO<sub>2</sub> capture capacity would increase from 7 MtCO<sub>2</sub>/year to nearly 13 MtCO<sub>2</sub>/year by 2028.

### Financing issues

Although the role to be played by CCUS in significantly reducing emissions in industries that are hard to decarbonize is acknowledged, there has been a hesitancy – particularly from oil and gas firms – to invest heavily in the technology. This is due to the belief that CCUS alone is not profitable, since it does not add reserves or increase the netback on a barrel of oil, two key balance sheet metrics for oil and gas firms. The Quest project cost CAD 1.35 billion, with up to CAD 865 million financed by the government for an estimated all-in cost of around CAD 80/tCO<sub>2e</sub>.

Beyond Quest, most carbon capture and storage (CCS) and CCUS projects in the oil and gas sector are small-scale and primarily targeted at EOR, where the CCUS pays for itself by delivering near-zero-cost oil that would not otherwise be extracted. EOR is largely restricted to facilities that can be connected to depleted wells, making it unattractive to oilsands miners as well as to most refineries.

Integrated projects like the ACTL, which delivers waste CO<sub>2</sub> streams from a fertilizer plant and upgrader/refinery to ageing reservoirs in central and southern Alberta, are an option. However, the likely exclusion of EOR as a designated use of captured CO<sub>2</sub> under the government’s investment scheme means that most new projects will be based on sequestration or carbon utilization.

This will be enabled by the significant cost reduction through learning that has occurred since Quest, which it is estimated would cost 30 per cent less if built today. The figure below illustrates the evolution of the capital cost for several key CCUS projects, in CAD/t CO<sub>2</sub> (Oxford Institute for Energy Studies 2021). The cost reduction is significant as compared to the Boundary Dam and Quest pioneering projects.

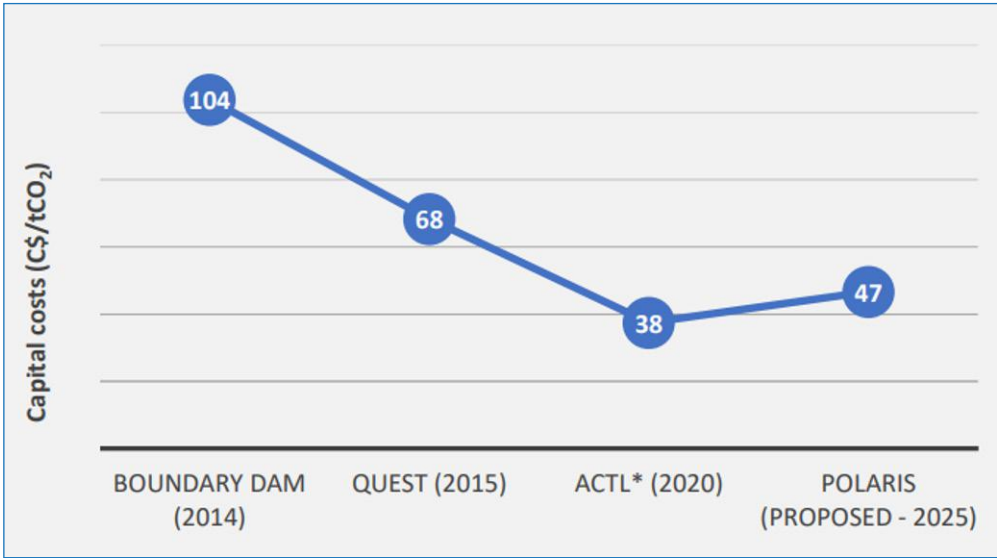


Fig. 13. Capital cost for CC(U)S facilities by project.

## Table of Contents

---

1.	National energy profile 2019 .....	312
2.	Energy perspectives 2030 - 2050 .....	315

## 1. National energy profile 2019

### Total yearly consumption: final energy, electricity (TWh)

Year	Energy Consumption (TWh)	Electricity Consumption (TWh)	Elec/Energy (%)
1990	82.0	14.2	17.3
1995	70.0	10.7	24.2
2000	76.5	12.6	16.5
2005	91.0	15.4	16.9
2010	89.6	16.9	18.9
2015	81.3	16.4	20.2
2019	84.5	17.2	20.3

Table 1. Total yearly consumption: final energy, electricity (TWh)

Electricity consumption has been increasing constantly since 1990 from 14.2 TWh all the way to 17.2 TWh in 2019. At the same time, total energy consumption declined from the 1990 level of 82 TWh to 1995 level of 70 TWh after which it again started increasing to reach a maximum value of 91 TWh in 2005. The share of electricity in final energy peaked in 1995 when it reached 24.2%. In 2000, the share of electricity was at an all-time low of 16.5%. Since then, it has been constantly increasing and reached 20.3% in 2019.

### Per capita yearly final energy and electricity consumptions (MWh)

Year	Inhabitants (per million)	Energy Consumption (TWh)	Energy Consumption per person and per year (MWh)	Electricity Consumption (TWh)	Electricity Consumption per person and per year (MWh)
1990	4.8	82.0	17.1	14.2	2.9
1995	4.6	70.0	15.2	10.7	2.3
2000	4.4	76.5	17.4	12.6	2.9
2005	4.4	91.0	20.7	15.4	3.5
2010	4.3	89.6	20.1	16.9	3.9
2015	4.2	81.3	19.4	16.4	3.9
2019	4.1	84.5	20.6	17.2	4.2

Table 2. Total yearly consumption per person: final energy, electricity (MWh per person per year)

The population of Croatia has been decreasing steadily since 1990 from 4.8 million to 4.1 million in 2019. The negative population trend is a result of negative natural growth and emigration to the rest of Europe. Total energy consumption declined from 82 TWh in 1990 to 70 TWh in 1995. It started rising again after the year 2000 and reached a peak of 91 TWh in 2005. Since then, it has been diminishing and reached 84.5 TWh in 2019. The decrease after 2005 was the result of an economic slowdown, a decline in population and the introduction of renewable energy and energy efficiency measures. Per capita energy consumption increased paradoxically alongside a decrease in population, which can be explained by the adoption of more electrical devices, which consequently also explains the similar trend in electricity demand.

### Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>), total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)

Year	Total CO <sub>2</sub> Emissions (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions from electricity (MtCO <sub>2</sub> )	CO <sub>2</sub> emissions per capita
1990	20.3	3.4	4.3
1995	14.8	2.4	3.2
2000	16.8	3.4	3.8
2005	19.9	4.2	4.6
2010	18.3	4.1	4.3
2015	15.4	3.3	3.7
2019	15.3	2.3	3.5

**Table 3.** CO<sub>2</sub> emissions – Total (MtCO<sub>2</sub>), from electricity (MtCO<sub>2</sub>), per capita (tCO<sub>2</sub>)

Tables are based and/or calculated from the following data International Energy Agency - Data and statistics

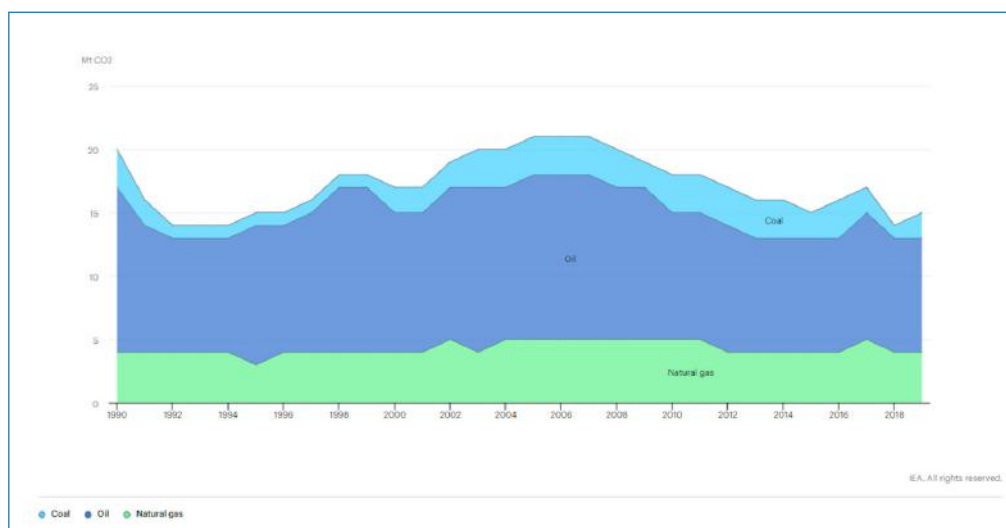
Explore energy data by category, indicator, country or region IEA (2021) Emission Factors

([https://www.iea.org/t\\_c/termsandconditions/](https://www.iea.org/t_c/termsandconditions/))

<https://www.worldometers.info/world-population/population-by-country/>

Croatia reduced emissions from 20,3 Mt in 1990 all the way to 15,3 Mt in 2019. The decrease in emissions in the first part of the observed timespan is due to subdued economic activity. The drop in the last 10 years is due to the transition of the economy to a service-based economy. In addition, the decline in the Croatian population is also partially responsible for the decline in emissions. The decrease of emissions from electricity generation is a result of the continued transition from fossil fuel power plants to the application of new renewable generating technologies.

### CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)



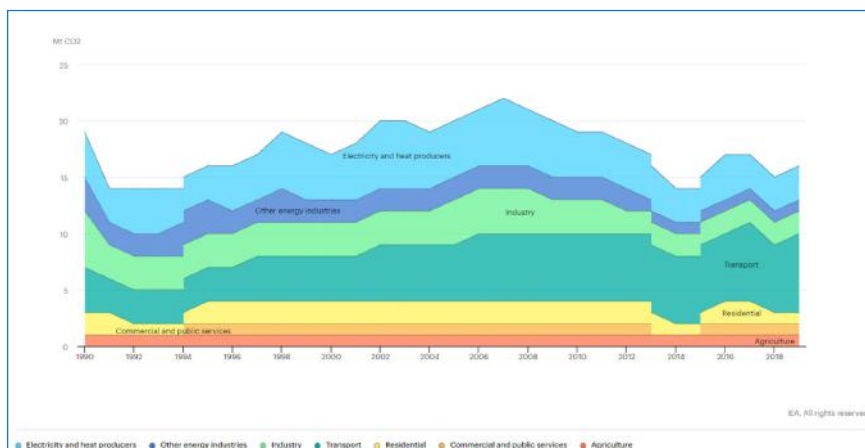
**Fig. 1.** CO<sub>2</sub> emissions by energy source Croatia 1990-2019

Data from IEA, Data & Statistics

<https://www.iea.org/data-and-statistics/data-browser?country=CROATIA&fuel=CO2%20emissions&indicator=CO2BySource>

The emissions from coal burning decreased right after 1990, from 3 Mt to 1 Mt of CO<sub>2</sub>, but they increased again in the period between 2003 and 2016 to 3 Mt. In the later years, the emissions from coal have not exceeded 2 Mt. Emissions originating from oil followed a similar path as they decreased from 13 Mt in 1990 to 9 Mt between 1992 and 1994. These emissions reached 2 peaks of 13 Mt each thereafter: one from 1998 to 1999, while the other was between 2003 and 2007. After 2008, the emissions from oil utilisation also decreased to a mostly stable level of 9 Mt since 2013. The natural gas-related emissions on the other hand have remained at a fairly stable level since 1990 at around 4 Mt with the exception of the period between 2002 and 2011, where they reached about 5 Mt/year.

## CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)



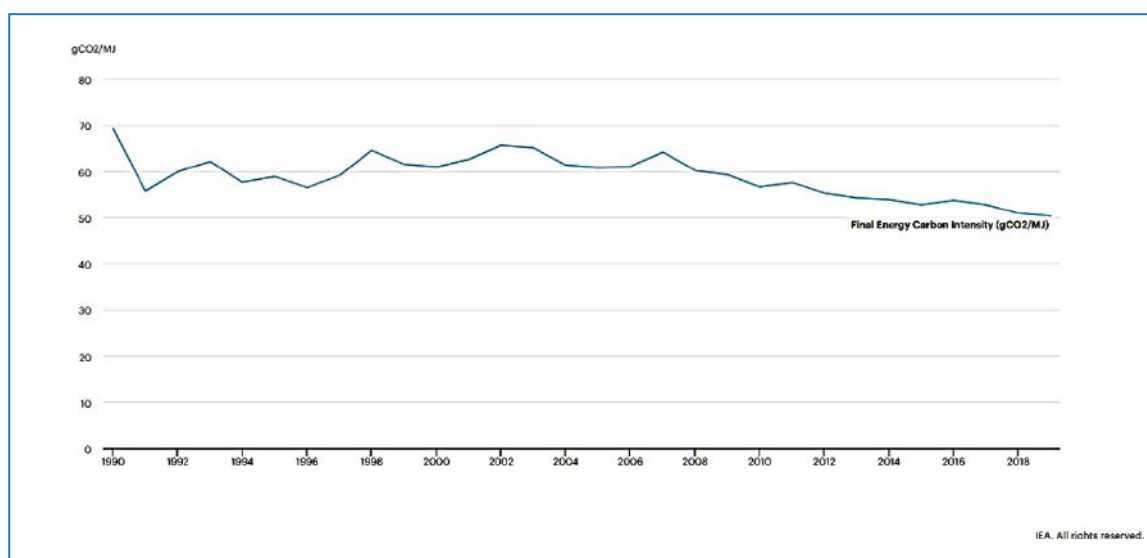
**Fig. 2.** CO<sub>2</sub> emissions by sector Croatia 1990-2019

Data from IEA, Data & Statistics

<https://www.iea.org/data-and-statistics/data-browser?country=CROATIA&fuel=CO2%20emissions&indicator=CO2BySector>

In the transport sector emissions increased from the levels of 4 Mt in 1990 to 7 Mt in 2019. The emissions from electricity and heat generation followed a different path: they have been increasing from 4 Mt in 1990 to 7 Mt in 2007 with a decrease thereafter to 3 Mt in 2019, partly due to the economic recession in 2008. As a consequence of the transition toward a service-based economy, there was also a noticeable reduction in emissions from the industry sector.

## Final energy carbon intensity: gCO<sub>2</sub>/MJ and gCO<sub>2</sub>/kWh (1 Megajoule = 0.27778 Kilowatt hours)



**Fig. 3.** Final energy carbon intensity Croatia 1990 - 2019

<https://www.iea.org/data-and-statistics/data-browser?country=CROATIA&fuel=CO2%20emissions&indicator=FECI>

Croatian final energy carbon intensity dropped from a value of 69.2 gCO<sub>2</sub>/MJ in 1990 to a value of 50.4 in 2019. Most of the decrease happened during the period after 2008.

## 2. Energy perspectives 2030 - 2050

If possible, give the national perspectives for 2030 and 2050 or the roadmap to 2030 and 2050 if they exist.

**Does your country have national roadmaps regarding energy production and GHG emissions? What legal status do these documents have? What is their timeline?**

Croatia's strategies and programmes related to the energy sector are under the authority of the Ministry of Economy and Sustainable development. The pertinent texts are available here: <https://mingor.gov.hr/o-ministarstvu-1065/djelokrug-4925/energetika/energetska-politika-i-planiranje/strategije-planovi-i-programi-2009/2009>. The most important documents are:

*Croatian energy strategy until 2030, with 2050 outlook*, period 2020-2050, accepted by the Government (see <https://mingor.gov.hr/UserDocImages/UPRAVA ZA ENERGETIKU/Strategije, planovi i programi/Strategija energetskeg razvoja RH 2030 s pogledom na 2050.pdf>) [in croatian]

*Integrated National Energy and Climate Plan for the Republic of Croatia*, period 2021-2030 (see [https://mingor.gov.hr/UserDocImages/UPRAVA ZA ENERGETIKU/Strategije, planovi i programi/NECP\\_Croatia\\_eng.pdf](https://mingor.gov.hr/UserDocImages/UPRAVA ZA ENERGETIKU/Strategije, planovi i programi/NECP_Croatia_eng.pdf)) [in english]

*Energy efficiency programme for the decarbonisation of the energy sector*, period 2019-2050 (see <https://mingor.gov.hr/UserDocImages/UPRAVA ZA ENERGETIKU/Dekarbonizacija energetske u%C4%8Dinkovitosti.pdf>) [in croatian]

*Croatian net-zero CO<sub>2</sub> energy strategy*, period 2020-2050 (see <https://mingor.gov.hr/o-ministarstvu-1065/djelokrug-4925/energetika/energetska-politika-i-planiranje/strategije-planovi-i-programi-2009/2009>) – Government acceptance pending. [in croatian]

### Roadmap for the energy mix

*The Croatian energy strategy until 2030 with 2050 outlook* proposes an energy mix by 2050 considering two scenarios: S1 – rapid energy transition, and S2 – moderate energy transition.

S1	2000	2010	2017	2030	2040	2050
H2	0.0	0.0	0.0	0.0	0.3	30.2
El energy	294.2	341.2	597.9	292.7	157.9	2.2
Non-renewable waste	1.3	7.6	11.5	10.6	10	8.1
RES	1 557.2	2 064.3	1 894.3	2 642.3	3 039.1	3 663.9
Natural gas	2 209.4	2 632.4	2 493.3	2 167.6	1 774.2	1 455.4
Oil	3 950.2	3 729.1	3 476.9	3 075.7	2 498.8	1 340.2
Coal	431.5	682.7	392.3	208.2	35.7	19.3
Total	8 443.8	9 457.3	8 866.2	8 397.1	7 516.0	6 519.3

Table 4. Consumption of primary energy allocated to fuel sources in scenario S1 (in ktoe)

S2	2000	2010	2017	2030	2040	2050
H2	0.0	0.0	0.0	0.004	0.2	15.9
El energy	294.2	341.2	597.9	335.4	160.2	2.1
Non renewable waste	1.3	7.6	11.5	10.6	10.0	8.1
RES	1 557.2	2 064.3	1 894.3	2 759.9	3 270.2	3 426.0
Natural gas	2 209.4	2 632.4	2 493.3	2 312.6	2 229.2	2 124.0
Oil	3 950.2	3 729.1	3 476.9	3 140.3	2 608.6	1 788.0
Coal	431.5	682.7	392.3	214.5	42.2	27.7
Total	8 443.8	9 457.3	8 866.2	8 773.304	8 320.6	7 391.8

Table 5. Consumption of primary energy allocated to fuel sources in scenario S2 (in ktoe)

## Roadmap for the GHG emissions (country, per capita)

GHG emissions projections are available in *Croatian NECP*, as shown below, with S1 and S2 scenarios previously explained.

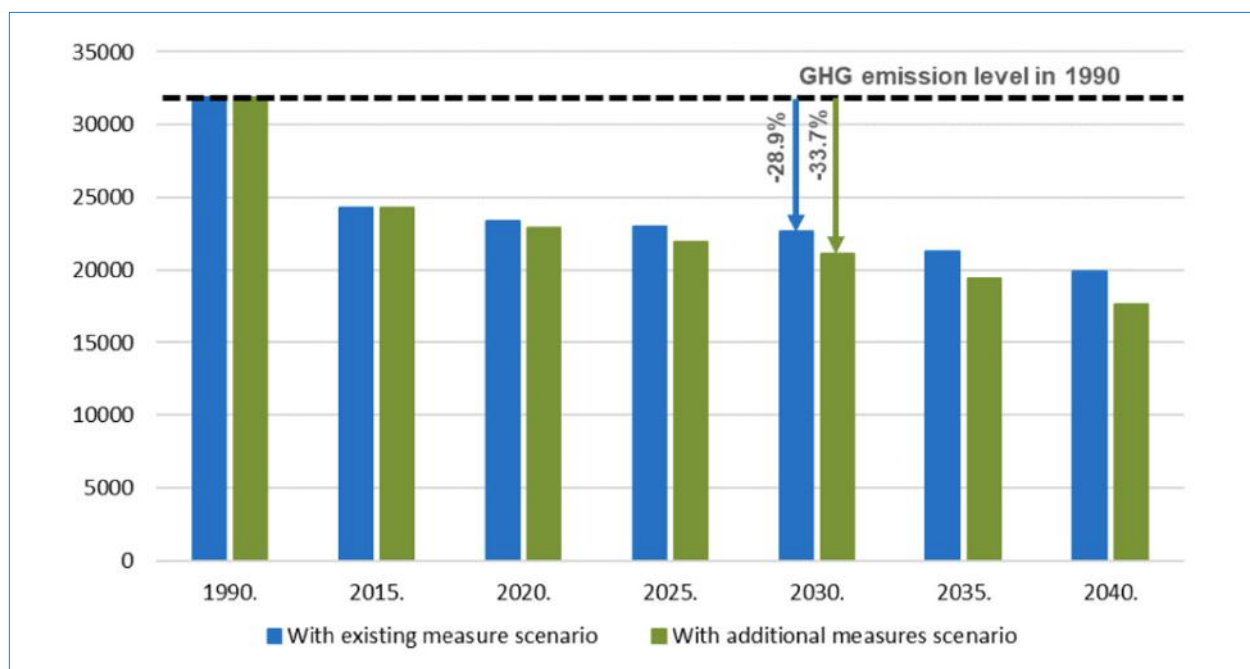


Fig. 4. GHG emissions according to the Croatian NECP (in kt CO<sub>2</sub>e)

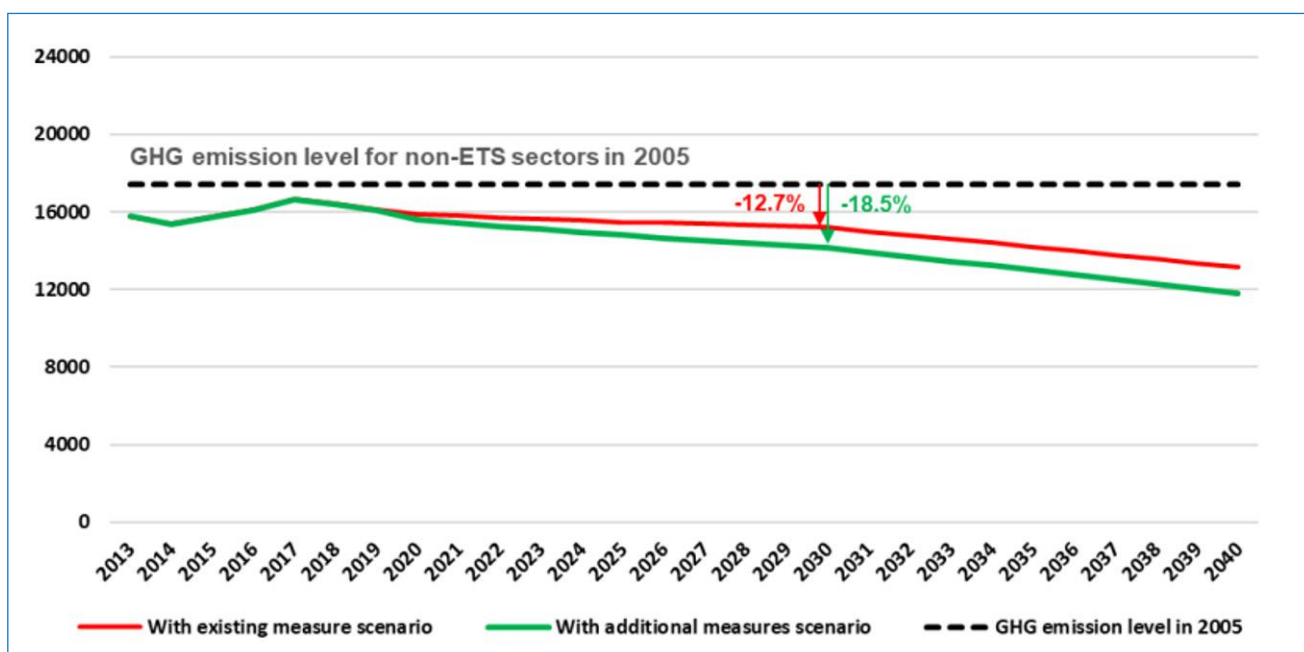


Fig. 5. Projection of greenhouse gas emissions from sectors outside of ETS, for the scenario with existing measures and the scenario with additional measures

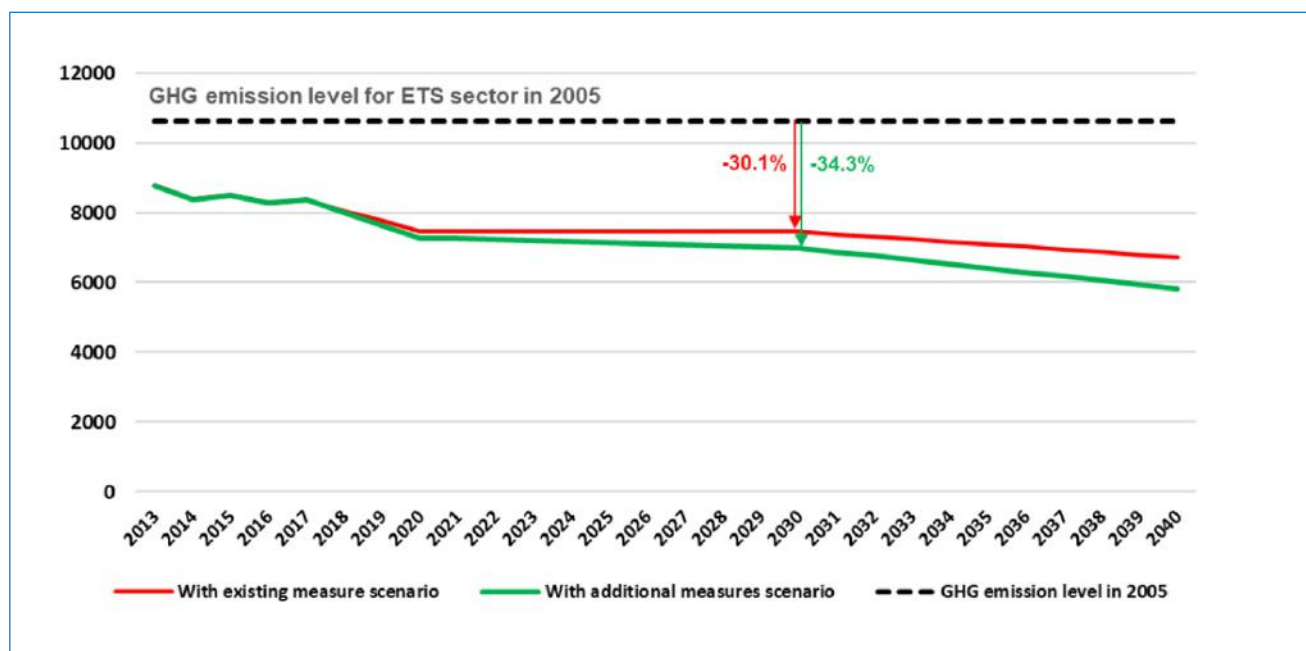


Fig. 6. Projection of greenhouse gas emissions from the ETS sector, for the scenario with existing measures and the scenario with additional measures

## Roadmap for the electricity mix

The *Croatian energy strategy until 2030 with 2050 outlook* presents the 3 scenarios of development of energy system. It sets the objective of reducing the emissions by 2030 in comparison to 1990 in the scenario S0 by 32.8%, in S1 by 37.5% and in S2 by 35.4%. By the year 2050, the planned reduction in S0 scenario is 49.3% in comparison to 1990 levels, in S1 by 74.4% and in S2 by 64.3%. Electricity generation from renewable energy is planned to increase to 60% in 2030 for the scenario S0, to 66% in S1 and to 61% in S2 scenario. For the case of 2050, the share of RES in electricity generation is planned to reach 82% in S0, 88% in S1 and 83% in S2 scenario.

The tables below present the electricity mix according to the *Croatian energy strategy until 2030 with 2050 outlook*.

S1	2000	2010	2017	2030	2040	2050
industrial CHP	559.8	446.8	414.2	320.3	280.4	239.8
public CHP	797.6	2 589.0	3 383.0	3 316.4	2 394.0	1 636.8
PP	3 270.1	2 494.8	1 395.9	719.8	0.0	1 764.3
Geothermal	0.0	0.0	0.0	128.8	365.8	427.8
Solar	0.0	0.1	78.7	1 371.0	3 316.0	5 133.1
Wind	0.0	139.1	1 204.0	4 331.6	7 183.7	10 563.2
Hydro	6 471.3	9 232.3	5 507.7	7 307.2	7 637.7	9 772.7
Total	11 098.8	14 902.1	11 983.5	17 495.1	21 177.6	29 537.7

Table 6. Electricity mix in S1 scenario (in GWh)

S2	2000	2010	2017	2030	2040	2050
industrial CHP	559.8	446.8	414.2	320.3	280.4	239.8
public CHP	979.6	2 589.0	3 383.0	3 508.0	3 971.5	1 399.7
PP	3 270.1	2 494.8	1 395.9	799.5	160.3	1 951.9
Geothermal	0.0	0.0	0.0	128.8	365.8	427.8
Solar	0.0	0.1	78.7	1 013.3	2 374.6	3 624.4
Wind	0.0	139.1	1 204.0	3 548.8	5 544.6	7 858.9
Hydro	6 471.3	9 232.3	5 507.7	7 319.2	7 702.5	8 244.3
Total	11 280.8	14 902.1	11 983.5	16 637.9	20 399.7	23 746.8

Table 7. Electricity mix in S2 scenario (in GWh)

## CO<sub>2</sub> emissions from electricity production

The specific CO<sub>2</sub> emissions of the Croatian power system are displayed in *Table 8*. The table displays 2 columns. One is dedicated to the carbon intensity of the energy consumed in Croatia, while the other is dedicated to the energy that is generated in Croatia. The values are sourced from the Croatian annual energy report – Energy in Croatia [2].

Year	For energy consumed in Croatia	For energy generated in Croatia
2015	148	236
2016	163	233
2017	131	207
2018	106	148
2019	121	179
2020	124	166

Table 8. Data on specific electricity sector emissions (gCO<sub>2</sub>/kWh)

## Energy balance (energy sources to end-uses)

Croatia's energy balances as Sankey diagram are shown below. The diagram is available via IEA here: <https://www.iea.org/sankey/#?c=Croatia&s=Balance>

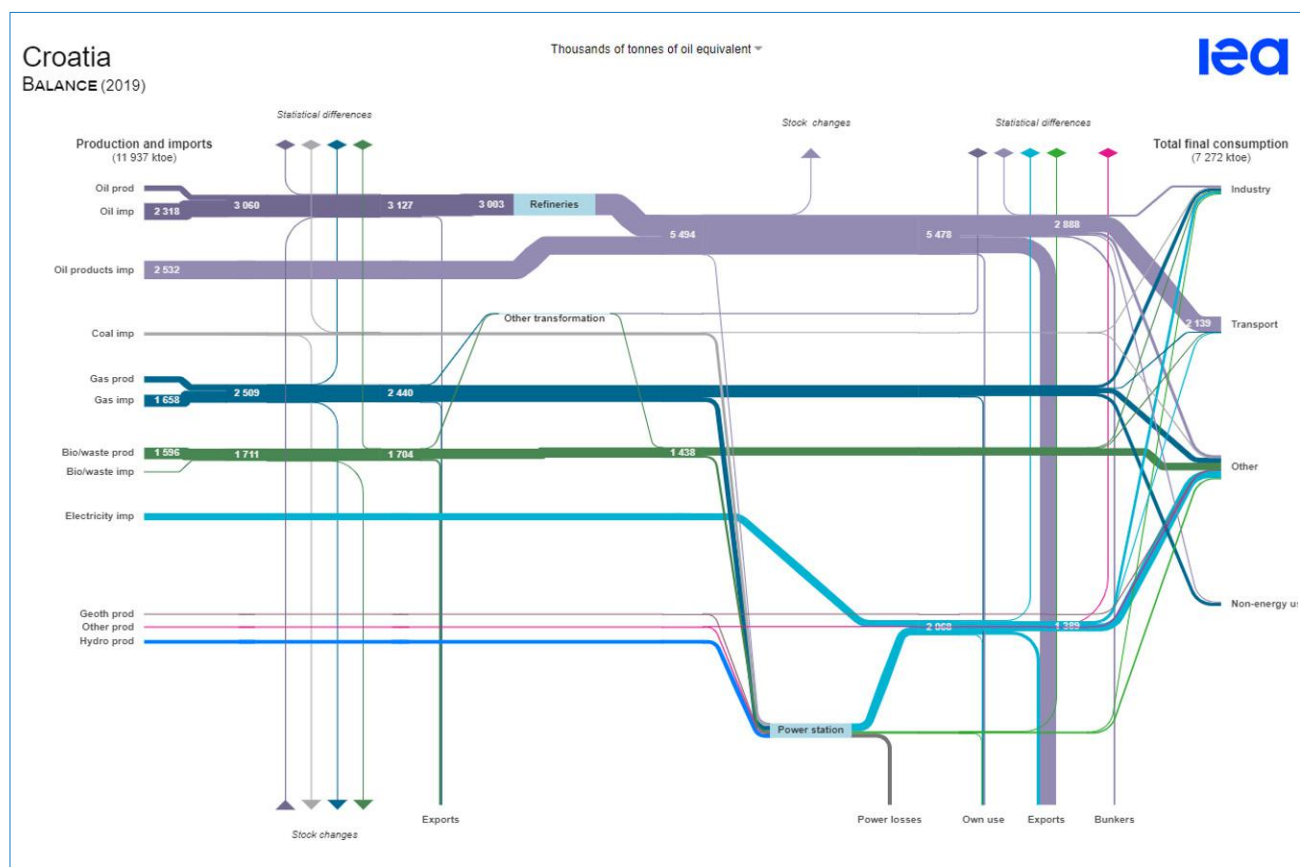


Fig. 7. Sankey diagram on Croatia's energy balance

## Table of Contents

---

<b>1.</b>	<b>National energy profile 2019</b>	321
<b>2.</b>	<b>Energy perspectives 2030 - 2050</b>	325
2.1.	Perspectives	325
2.2.	France Energy Legislation.	331
2.3.	Two Case Studies on biomasse.	332

## 1. National energy profile 2019

### Total yearly consumption: final energy, electricity (TWh)

Year	Energy Consumption (TWh)	Electricity Consumption (TWh)	Elec/Energy (%)
1990	1 647	348	21.1
1995	1 758	394	22.4
2000	1 878	440	23.4
2005	1 949	484	24.8
2010	1 858	503	27.1
2015	1 791	479	26.8
2019	1 745	475	27.2

**Table 1.** Total final energy and electricity consumption by year

<https://www.iea.org/data-and-statistics/data-tables?country=FRANCE&energy=Balances&year=2019>

and: <https://www.iea.org/data-and-statistics/data-browser/?country=FRANCE&fuel=Energy%20consumption&indicator=TotElecCons>

During this period three main factors of the evolutions have been: (a) a slow increase of the population from 58.2 million to 67.2 million (+ 15.5%), (b) a decrease of the industry, (c) some effort on energy efficiency. The result is a 6% increase of final energy consumption over the period 1990-2019.

Concerning the electricity, after an increase of around 40% between 1990 and 2010, the consumption has been stabilize and slightly decreasing from 2010 to 2019.

As in the other countries, the heavy trend is an increase of the ratio electricity consumption/final energy consumption. France has a bit higher ratio than many other European country, partially since electric heating has been more developed to reduce oil imports in the 70's.

### Per capita yearly final energy and electricity consumptions (MWh)

Year	Final energy consumption/capita MWh/year	Electricity consumption per capita MWh
1990	28.3	6.0
1995	29.6	6.6
2000	30.8	7.2
2005	30.8	7.7
2010	28.6	7.7
2015	26.9	7.2
2019	25.9	7.0

**Table 2.** Per capita yearly final energy and electricity consumptions

Data from IEA, Key World energy Statistics, Selected indicators.

### Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>), total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)

Year	Total CO <sub>2</sub> Emissions (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions from electricity (MtCO <sub>2</sub> )	CO <sub>2</sub> emissions per capita
1990	345	-	5.93
1995	344	36 572	5.77
2000	365	41 576	5.99
2005	372	46 084	5.89
2010	340	44 973	5.23
2015	305	32 456	4.50
2019	294	30 254	4.36

**Table 3.** Total CO<sub>2</sub> emissions, from electricity production, and per capita by year

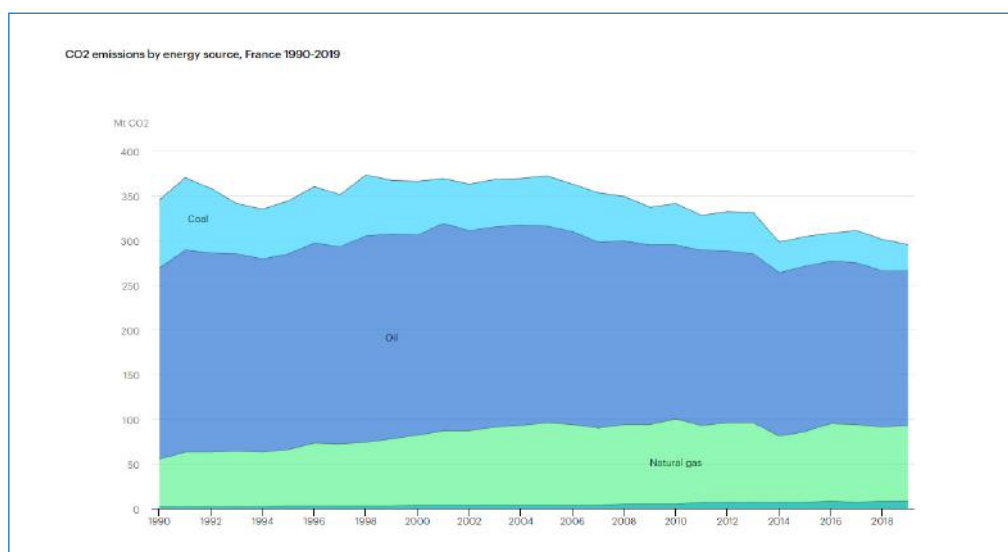
Data from IEA, Data & Statistics <https://www.iea.org/data-and-statistics/data-browser/?country=FRANCE&fuel=CO2%20emissions&indicator=TotCO2> (for 1990-2015)

IEA CO<sub>2</sub> emissions from fuel combustion 2019 Highlights (for 1990-2015)

IEA Key World Energy Statistics 2019 for 2019 data

The important emissions reduction this last 10 years is the consequence of a decrease of industry on one side, and the shutdown of coal plants on the other side. The emissions level per capita is low compared to many other industrialized countries since the electric mix is largely decarbonated with nuclear and hydraulic generation.

### CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)



**Fig. 1.** CO<sub>2</sub> emissions by fossil energy source

Data from IEA, Data & Statistics

<https://www.iea.org/data-and-statistics/data-browser/?country=FRANCE&fuel=CO2%20emissions&indicator=CO2BySource>

As in many other OECD countries, the use of coal has been significantly reduced, the use of oil slightly decreasing but the use of natural gas has been increasing.

## CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)

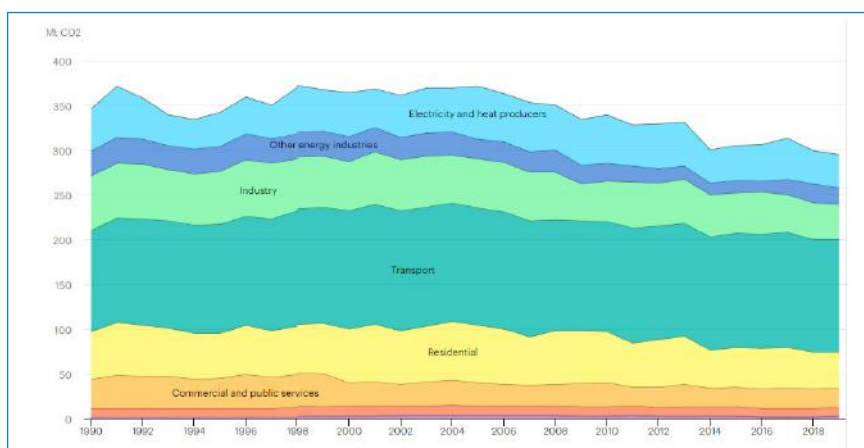


Fig. 2. CO<sub>2</sub> emissions by sector

Data from IEA, Data & Statistics

<https://www.iea.org/data-and-statistics/data-browser/?country=FRANCE&fuel=CO2%20emissions&indicator=CO2BySector>

The increase of the emissions due to transport are visible on this diagram. The “Electricity+heat” sector doesn’t decrease, but the emissions from electricity are decreasing (see *Total CO<sub>2</sub> emissions*, *CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>)*, *total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)*, page 320322) and the emissions from heat are increasing.

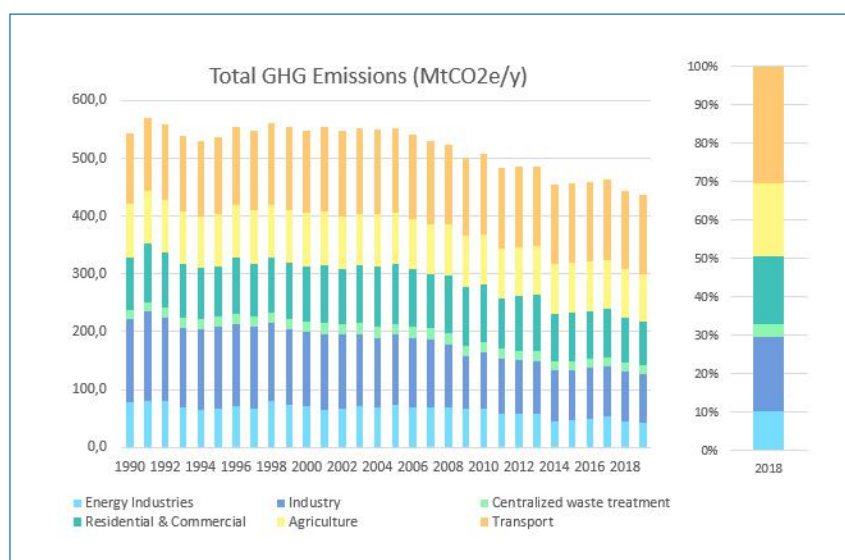


Fig. 3. Total CO<sub>2</sub> emissions by sector including agriculture

The following detailed text refers to Fig.3., which includes emissions from agriculture.

In 2018, France's territorial emissions were 445 MtCO<sub>2e</sub> compared to 546 MtCO<sub>2e</sub> in 1990 (excluding the land sector); they have therefore decreased by 18.5% over this period, i.e. a decrease of around 0.7% per year, and their per capita level is now one of the lowest among developed countries (6.4 tCO<sub>2e</sub>/cap). In particular, 2018 saw a 4.2% decrease in emissions compared to 2017.

In France, national GHG emissions (excluding LULUCF carbon sinks) were at an average level of 554 Mt CO<sub>2e</sub> between 1990 and 2005. After a period of decline between 2005 and 2014 (-2.2%/year on average), emissions had undergone a slight increase (+0.7%/year on average) between 2014 and 2017, due especially to transport and heating.

Since 2018, emissions are again decreasing (-4% in 2018, -1% in 2019), a trend that should continue in 2020 given the Covid-19 crisis. Emissions in 2018 (445 Mt CO<sub>2e</sub>) and 2019 (436 Mt CO<sub>2e</sub>) are at the lowest levels

recorded since 1990.

In 2018, 31% of GHG emissions were related to the transport sector, 19% to agriculture, 19% to the residential-tertiary sector, 18% to manufacturing and construction, 10% to the energy industry, and 3% to waste. However, only six sub-sectors are responsible for half of the GHG emissions: diesel passenger vehicles (11.7%), residential (heating..., 10.9%), tertiary (heating, refrigeration..., 7.8%); cattle breeding (7.7%); diesel heavy-duty vehicles (6.4%) and diesel light-duty vehicles (5.4%). The notable decreases between 2017 and 2019 correspond to the energy (-29% from electricity production), residential-tertiary (-9%), agriculture (-2%) and waste (-5%) sectors.

France's National Low-Carbon Strategy (SNBC) sets France's climate objectives. For each four-year period, emissions must not exceed a given carbon budget on average over the period.

The first carbon budget (2015-2018) was not respected. The average annual carbon budget for the period 2019-2023, set in 2020 by the revised SNBC, is 422 MtCO<sub>2e</sub>/year. The indicative annual budget for 2019 was 443 Mt CO<sub>2e</sub>, while the provisional estimate of 2019 emissions was 436 Mt CO<sub>2e</sub>. If this pre-estimate is confirmed by the 2019 consolidated inventory, the year 2019 would therefore meet the target.

Emissions will still have to decrease in the following years by nearly -10 Mt CO<sub>2e</sub> on average per year (i.e. -2.3%/year) for the 2<sup>nd</sup> carbon budget to be respected on average over the period. Even if the emissions for the year 2020 are not yet estimated, the effects of the measures to fight against Covid-19 could lead to a -5% to -15% decrease in GHG emissions in 2020, even if these are very provisional approximations at this stage.

### *Refineries-related emissions*

Between 1990 and 2017, emissions directly related to oil refining in France decreased by 37.3%. However, this decrease is largely due to the closure of four refineries and the decrease in the net production of finished products in France, compensated by higher imports, given the strong demand for diesel fuel, which cannot be met without costly adaptation of the production tool. It is therefore not necessarily significant from the point of view of climate change mitigation.

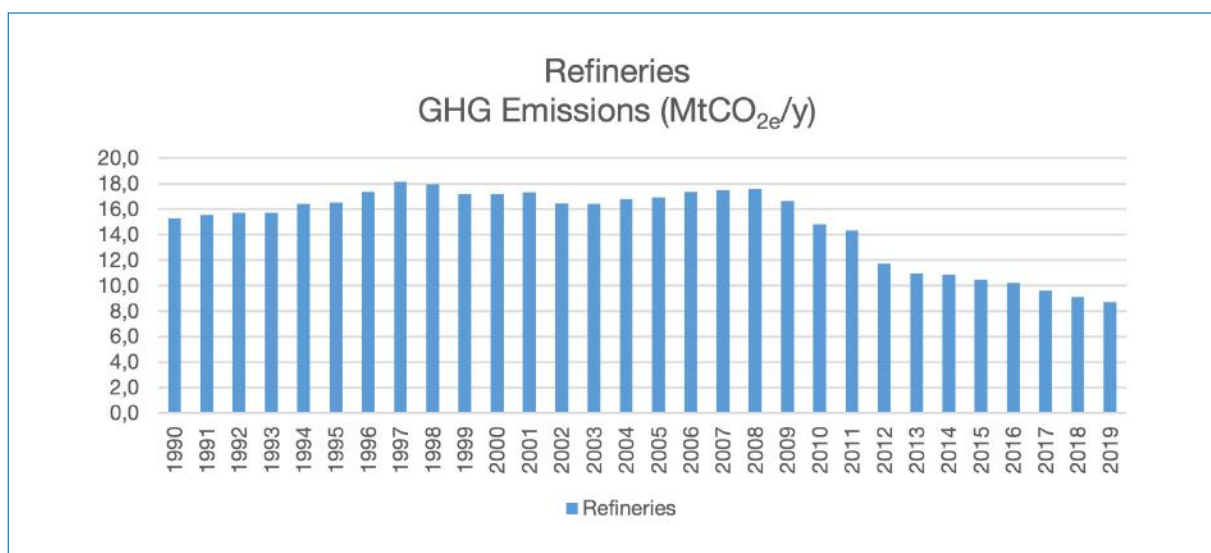


Fig. 4. Refineries GHG emissions

## Final energy carbon intensity: gCO<sub>2</sub>/MJ and gCO<sub>2</sub>/kWh (1 Megajoule = 0.27778 Kilowatt hours)

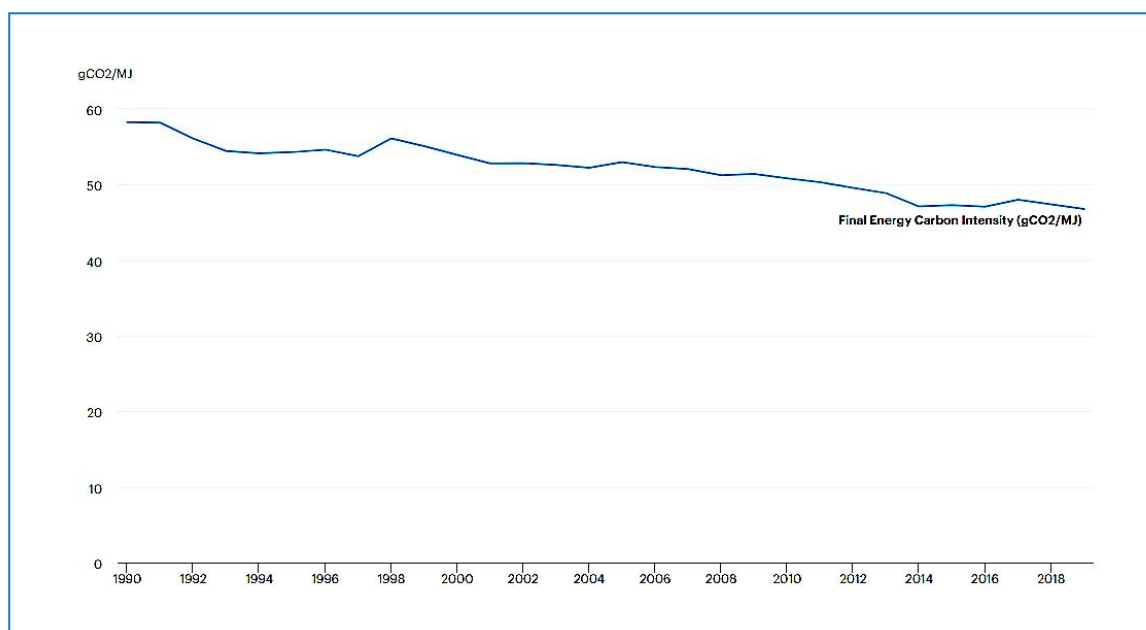


Fig. 5. Final energy carbon intensity, France 1990-2019

Data from IEA, Data & Statistics <https://www.iea.org/data-and-statistics/data-browser/?country=FRANCE&fuel=CO2%20emissions&indicator=FECI>

## Electricity Carbon intensity: gCO<sub>2</sub>/kWh

The CO<sub>2</sub> intensity of electricity has always been low due to the important share of nuclear electricity generation capacity, and also the contribution of hydroelectricity. The values were: 108 g in 1990, 77 g in 2000, 50 g in 2020. This decrease was largely consequence of the phasing out of most of the coal plants and also to the increase of wind and solar electricity this last years.

## 2. Energy perspectives 2030 - 2050

### 2.1. Perspectives

France's national outlook for 2030 and 2050 is presently governed by the Energy and Climate Law of November 8, 2019.

This law has been translated into operational rules by means of the *Multiannual Energy Programming* (long-term energy planning) and the *National Low Carbon Strategy*, both issued by government orders of April 21, 2020.

They are integrated in an "Energy code".

It sets a long-term trajectory for the energy mix, as well as the priorities for action regarding the role of the various forms of energy on the continental metropolitan territory, in order to achieve the national objectives, set by the law (specific evolving programmes exist for France's overseas territories).

The *National Low Carbon Strategy* is France's roadmap for achieving its greenhouse gas emission reduction targets (-40% by 2030 [1990 base] and carbon neutrality by 2050, in accordance with article 1 of the Energy and Climate Law). It defines the guidelines and concrete measures to be implemented in public, sectoral and territorial policies. It sets short- and medium-term carbon budgets (GHG emission ceilings not to be exceeded at national level over five-year periods) to define the emission reduction trajectory to be followed.

## Does your country have national roadmaps regarding energy production and GHG emissions?

### What legal status do these documents have? What is their timeline?

As mentioned above, law-specific objectives are to reduce greenhouse gas emissions by 40% between 1990 and 2030 and achieve carbon neutrality by 2050 by dividing greenhouse gas emissions by a factor of more than six.

*Multiannual Energy Programming* and *National Low Carbon Strategy* timelines are 5 years. The updated French Energy-Climate Strategy will be the roadmap to reduce GHG emissions and adapt French society to the impacts of climate change. It brings together:

- The *Energy-Climate Programming Law*;
- The *National Low Carbon Strategy*;
- The *Multiannual Energy Programming*;
- The *National Plan for Adaptation to Climate Change*.

The *Energy-Climate Programming Law* is due to be issued by July 2023 and the corresponding *Multiannual Energy Programming* and *National Low Carbon Strategy* 12 months thereafter.

As the new *French Energy-Climate Strategy* is due to be issued by the end of 2023, it has to be presented to parliament by end of 2022.

### Roadmap for the energy mix

Targets for final energy consumption and reduction of such (see *Electricity Carbon intensity: gCO<sub>2</sub>/kWh*, page 325 for historical final energy by end users)

	2017	2023	2028
Final energy consumption (TWh)	1 634	1 525	1 378
% reduction vs.2012	0.9%	7.6%	16.5%

Table 4. Past and projected final energy consumption 2017 - 2028

The Energy code set the following for 2030 for energy: 33% renewables, 38% for heat consumption, 15% for fuels, 10% for gas and 40% for electricity. Fit for 55 impose 40% of renewable for 2030. Therefore, the *Multiannual Energy Programming* shall be revised to take Fit for 55 into account.

### Roadmap for the GHG emissions (country, per capita)

The present roadmap for the GHG emissions in the present National Low Carbon Strategy defines the next three carbon budgets as follows

Mean yearly emission (Mt CO <sub>2e</sub> )	Reference 1990	Reference 2005	Reference 2015	2019-2023	2024-2028	2029-2033
Total excluding LULUCF <sup>1</sup>	546	553	458	422	359	300
Total with LULUCF	521	505	417	383	320	258

Table 5. Past and projected GHG emissions for France from 1990 to 2033

### Roadmap for the electricity mix

The Climate and Energy Law sets the objective of reaching a nuclear share of 50% in the electricity mix by 2035. The objective is thus included in the Energy Code.

The table below presents the electricity mix in TWh that the *Multiannual Energy Programming* will make possible in 2023 and 2028 when the measures therein defined are adopted (scenario A and B are slight differing scenarios of the *Multiannual Energy Programming*).

<sup>1</sup> Land Use, Land-Use Change and Forestry (LULUCF)

TWh		Realised 2019	2023	2028 Scenario A	2028 Scenario B
<b>Nuclear</b>		379.4	393.0	382.0	371.0
<b>Fossil</b>	Coal	1.6	0.0	0.0	0.0
	Fuels	41.0	34.0	32.0	32.0
	Gas				
<b>Renewable</b>	Hydro	60.0	62.0	62.0	62.0
	On shore wind	33.7	52.0	77.0	81.0
	PV	11.6	24.0	43.0	53.0
	Bioenergy	9.7	9.0	9.0	10.0
	Offshore wind	0.0	9.0	20.0	21.0
<b>Total</b>		537.0	583.0	625.0	630.0

**Table 6.** Present and future electricity mix up to 2028, Scenario A and B

Taking into account the recent announcement of the French President concerning nuclear energy, one can assume that the closure of 12 nuclear plants by 2035 as forecast in the *Multiannual Energy Programming* to bring nuclear power down to 50% of the electricity mix, might be cancelled. One might also assume, taking into account the results of the “Energetic future 2050” study of RTE (the French Transmission and System Operator (TSO)) - with 6 scenarios – that the 2050 roadmap defined by present or future French governments will include nuclear as a large part of the electrical mix in 2050.

### CO<sub>2</sub> emissions from electricity production

The present French electricity sector is an atypical system: 93% decarbonised - 20 MtCO<sub>2</sub> equivalent in 2019.

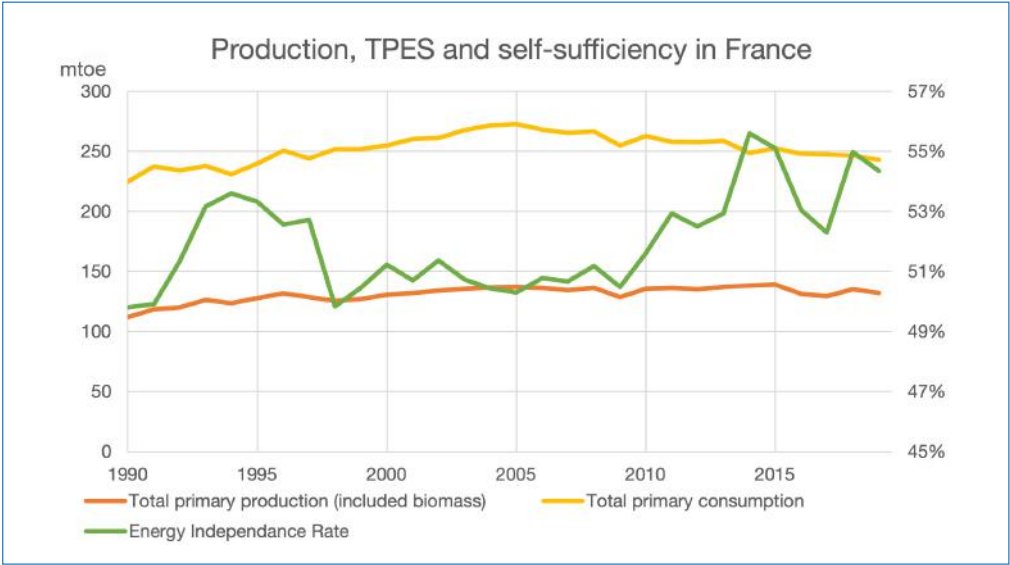
### Energy balance (energy sources to end-uses)

France Energy Balance (Enerdata 2019) in million tonnes of oil equivalent (mtoe). 1 mtoe = 11,63TWh.

Mtoe	Coal, Lignite	Crude oil	Oil products	Gas	Hydro, Nuclear,	Power	Heat	Bio-mass	Total
<b>PRIMARY PRODUCTION</b>	0.00	0.92		0.01	113.10		0.40	17.49	131.93
<b>Imports</b>	7.20	49.59	45.53	48.66		1.35	0.00	1.68	154.00
<b>Exports</b>	0.00	-0.08	-17.39	-9.68		-6.31	0.00	-0.96	-34.43
<b>Aviation and marine bunkers</b>	0.00	0.00	-7.69	0.00				0.00	-7.69
<b>Stock variations</b>	0.06	0.18	0.20	-1.55				0.09	-1.03
<b>PRIMARY CONSUMPTION</b>	7.25	50.61	20.65	37.44	113.10	-4.96	0.40	18.29	242.79
<b>Refineries</b>	0.00	-52.29	51.79	0.00		0.00	0.00	0.00	-0.50
<b>Power plants</b>	-1.49	0.00	-1.54	-6.55	-113.10	48.71	2.52	-4.46	-75.92
<b>Own use, losses*</b> * Including returns and transfers and heating plants.	-2.73	1.68	-5.21	-2.76		-6.40	1.13	-1.20	-15.48
<b>FINAL CONSUMPTION</b>	3.02		65.69	28.13		37.35	4.06	12.63	150.89
<b>Industry</b>	2.73		2.47	9.07		10.52	1.70	1.69	28.18
<b>Transport</b>	0.00		41.20	0.09		0.82	0.00	3.45	45.57
<b>Other sectors, including</b>	0.06		10.08	17.67		26.01	2.36	7.49	63.67
<b>Residential</b>	0.02		4.40	10.37		13.57	1.49	6.74	36.59
<b>Tertiary</b>	0.04		2.49	7.07		11.71	0.85	0.57	22.72
<b>Agriculture</b>	0.00		3.17	0.24		0.72	0.03	0.18	4.34
<b>Non energy uses</b>	0.23		11.94	1.29		0.00	0.00	0.00	13.47

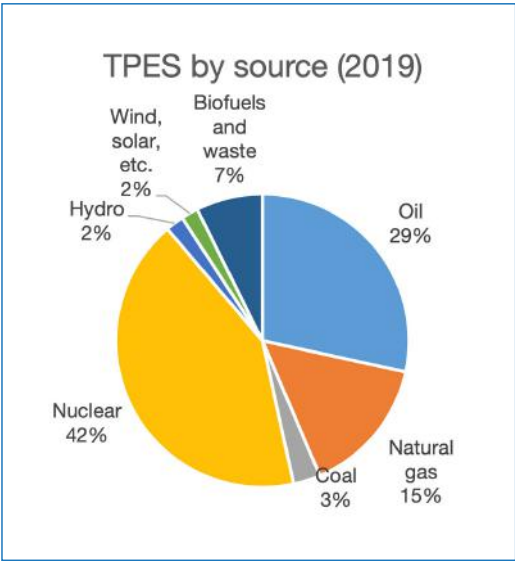
**Table 7.** Present (2019) energy balance for various energy sources and by sector  
**Source:** Enerdata [www.enerdata.net](http://www.enerdata.net) Historical final energy sources for end users

The above table shows clearly that coal does not play a significant role in the energy balance anymore, while oil & gas on one hand and nuclear & hydropower on the other hand provide almost equal amounts of energy for consumption. Biomass has become a significant energy vector.



**Fig. 6.** Energy production and self-sufficiency  
*Source:* Enerdata Since the 1980s, France produces half of the energy the country consumes, due to the development of the nuclear sector.

The source of energy production is shown in the chart below.



**Fig. 7.** Energy production by source

The chart below shows the evolution over time of the various energy sources with fossil fuels slowly declining and renewables gaining.

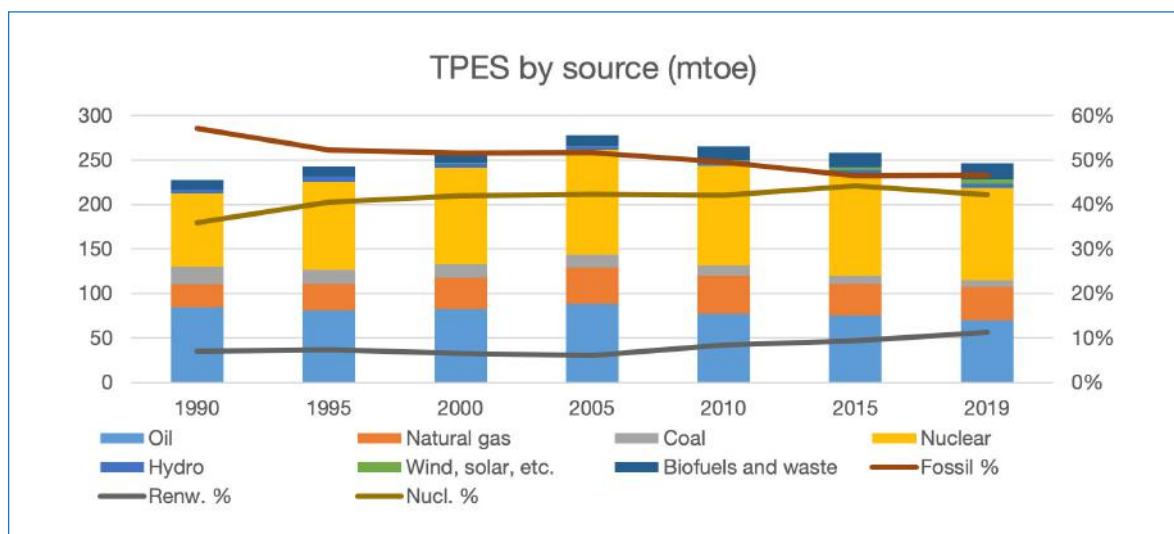


Fig. 8. Evolution of sources for energy production

France's total primary energy supply (TPES) was 246 million tonnes of oil-equivalent (Mtoe) in 2019. Since the peak of 277.8 Mtoe in 2005, TPES contracted by 11.3%.

Nuclear accounts for 42% of TPES in 2019, the largest share of nuclear in TPES in the World.

Fossil fuels accounted for 47% of TPES, made up of oil (29%), natural gas (15%) and coal (3%). This share was 52% in 2000 (declining by 0.8% per year since).

Renewable energy sources accounted for 11% of TPES, made up of biomass and waste (7%), hydro (2%), wind and solar and others (2%). TPES from renewable energy grew by 2.7% per year over the 2010-2019 period.

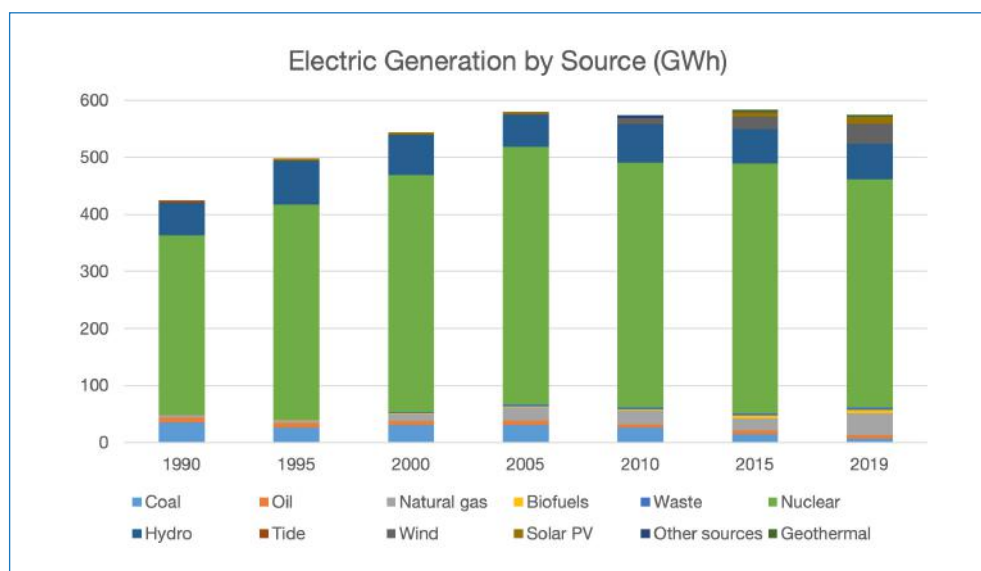


Fig. 9. Evolution of sources for electricity production

- France has a very low-carbon electricity mix owing to its large nuclear fleet, the second-largest after the United States. France is the world's largest net exporter of electricity
- France derives about 70% of its electricity from nuclear energy, due to a long-standing policy based on energy security. Government policy is to reduce this to 50% by 2035.

- There are currently 56 Operable Reactors for a total capacity of 61,370 MWe and one reactor in construction (Flamanville) with a capacity of 1,630 MWe
- In October 2014 the Energy Transition for Green Growth bill was passed by the National Assembly and so went onto the Senate. This set a target of 50% for nuclear contribution to electricity supply by 2025, and capped nuclear power capacity at 63.2 GWe, the level at the time. This meant that EDF would have to shut at least 1.650 GWe of nuclear capacity when its Flamanville 3 EPR starts commercial operation. The bill also set long-term targets to reduce greenhouse gas emissions by 40% by 2030 compared with 1990 levels, and by 75% by 2050; to halve final energy consumption by 2050 compared with 2012 levels; to reduce fossil fuel consumption by 30% by 2030 relative to 2012; and to increase the share of renewables in final energy consumption to 32% by 2030. The Senate early in 2015 amended the bill to remove the nuclear cap, but this was not accepted in the lower house. The National Assembly approved the bill including 970 amendments in July 2015, but with the 63.2 GWe nuclear cap and only 50% nuclear supply by 2025. In October 2016 the government postponed until after the 2017 presidential and National Assembly elections any decision on which, if any, reactors would close in order to reduce the nuclear share to 50%. In 2017 France postponed its 2025 target for reducing the share of nuclear to 50%. In December 2017 the French President stated that nuclear is "the most carbon-free way to produce electricity with renewables." In November 2018, a draft of the country's new energy plan confirmed that 2035 was the new target date for the reduction of nuclear's share to 50%. The plan states that 14 of the country's nuclear reactors will shut down by 2035, 4-6 of those by 2030. However, the plan also states that the option to build new nuclear reactors remains.

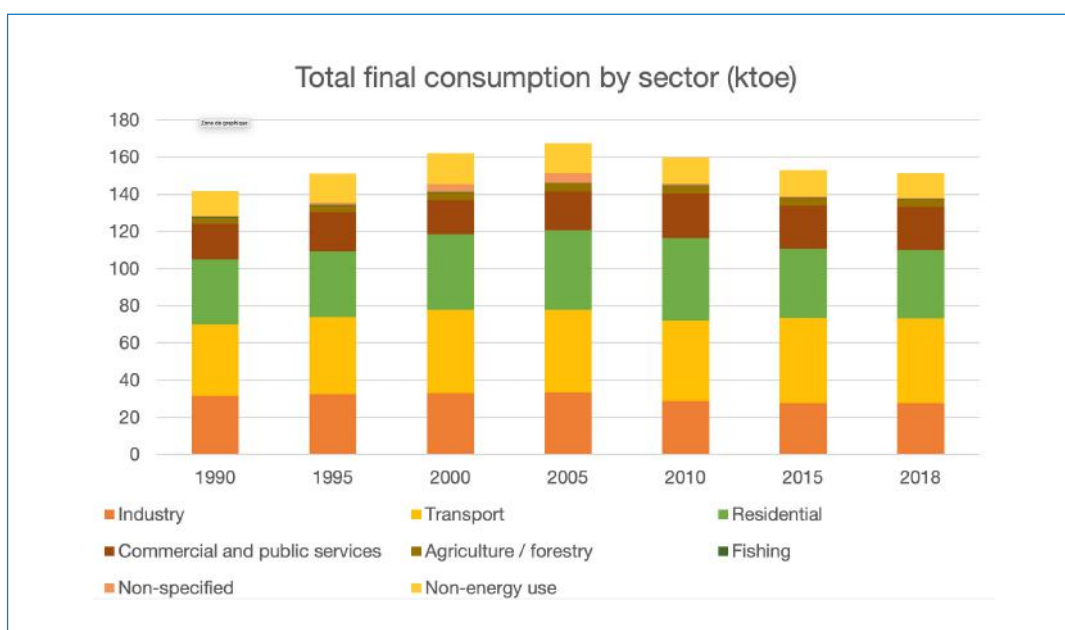


Fig. 10. Evolution of final energy consumption by sector

Transport is the largest consuming sector and accounted for 30% of TFC in 2018, or 45.3 Mtoe. The industrial and residential sectors represented 18% and 24%, respectively, while the commercial sector consumed 15%.

Since 2000, TFC has declined by 6.7% reflecting the structurally weak economic growth and energy efficiency progress in residential and commercial and services sectors.

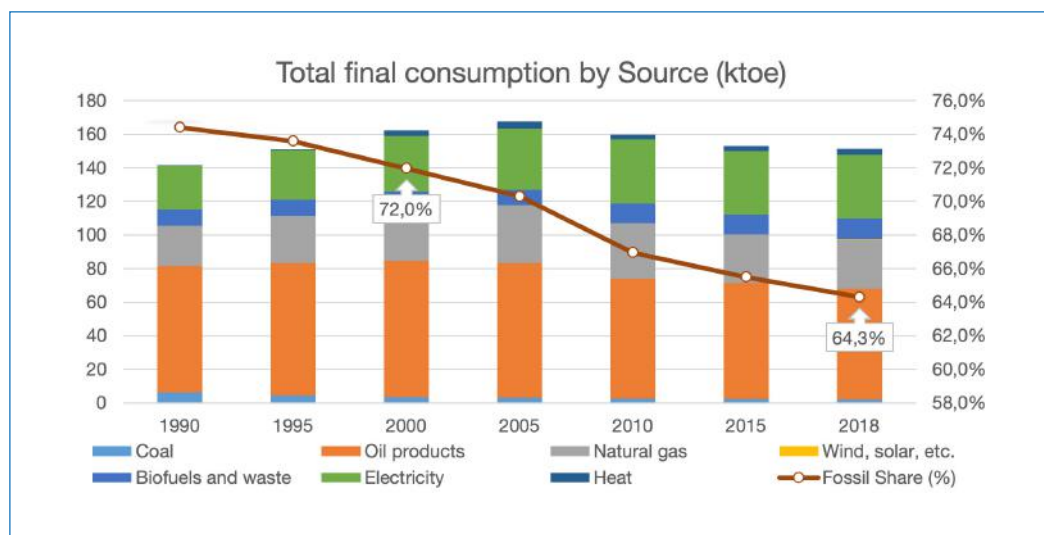


Fig. 11. Evolution of final energy consumption by source

Fossil energy represents 64% of TFC in 2018, vs. 72% in 2000 as coal consumption has been slashed by almost 40%, and oil products by 18.6%.

## 2.2. France Energy Legislation

From a legal point of view, France's energy law is ruled under both European Union law and national law. France energy policy and strategy is now grounded on two pillars, introduced by the 2015 energy transition for green growth Act (LTECV): **the SNBC** and **the PPE**. Both were adopted in April 2020. France also released, in April 2020, its national energy and climate plan (**NECP**) in compliance with the European Union Regulation on governance of the energy union and climate action (EU/2018/1999).

**The PPE** (decree n02020-456) establishes the priorities in terms of energy policy for public actors to reach the objectives set by the LTECV and the LCE and has a significant impact on the national energy strategy. It is legally binding, so that the strategies and planning documents which include energy guidance (i.e. regional climate, air quality and energy plans) must be consistent with the PPE. The PPE notably aims at reducing the final energy consumption by 7.6% in 2023 and 16.5% in 2028 (compared to 2012). The PPE also aims at shutting down the last coal plants by 2022 and 14 out of the 58 existing nuclear reactors by 2035 including those of the Fessenheim plant. As for renewable energies, the PPE sets ambitious targets for each source and an indicative timeframe for the launch of calls for tenders for renewable energy plants. For instance, by 2023, the installed power must reach 24.1 GW for onshore wind energy, 20.1 GW for photovoltaic energy (five times the current installed power), 25.7 GW for hydropower and 2.4 GW for offshore and floating wind power. For the latter, five calls for tenders will be organised in the upcoming three years.

**The SBNC** (decree n02020-457) defines cross-cutting and sectoral objectives to conduct France's policy in terms of GHG emissions in the long-medium run. This non-binding document has set "carbon budgets", i.e. national emissions thresholds on five-year terms, broken down into sectoral activities. The 2020 SNBC was subject to a public participation procedure. One of the main objectives of the 2020 SNBC is, by 2050, to reduce the GHG emission in the industry sector by 81% comparing to 2015.

**NECP** - The European Union has laid down targets for 2030 that its Member States shall reach. The latter was expected to notify to the Commission their NECP for 2021-2030, which must describe national objectives and national climate-energy contributions as well as policies and measures planned or adopted to implement them. Therefore, the French NECP outlines France priority actions in the energy sector for the next decade and mainly relies on the PPE and the SNBC mentioned hereabove.

### Recent developments in legislation

The end of 2019 and, moreover, 2020 have seen major evolutions in terms of French legislation and regulation applying to the energy sector. A wide range of legal texts were adopted, notably starting with the LCE on November 2019 and followed by several ordinances issued by the government.

**The LCE** (Loi Energie Climat) was drafted following the law n°2015-992 related to LTECV as well as the Paris Agreement in 2015, and now constitutes the pillar of France's energy policy. It aims at ensuring the implementation of the French national and international commitments as well as reaching the goals assigned by the SNBC and the PPE (cf. hereabove), in accordance with the EU Clean Energy Package adopted on November 30, 2016 by the European Commission. Among these goals, France notably targets the **"carbon neutrality" by the end of 2050** (by dividing its GHG emissions by six in comparison to 1990 (instead of four in the LTECV), but delays for 2035 regarding the goal of cutting the share of nuclear energy of the electricity production (previously set to 2025 by the LTECV). It also raised the target related to the share of energy from renewable sources in gross final consumption up to 33% by 2030. The LCE is also noticeable as it addresses the transposition of the EU Clean Energy Package and provides further mechanisms to foster the development of renewable energies.

**Law on the orientation of mobilities (LOM)** - The LOM n°2019-1428 was adopted in December 2019. Although less important in terms of energy policy than the LCE, it sets ambitious objectives for the energy transition in the transport sector. For instance, the law forbids the sale of cars using carbon-based fossil fuels by 2040 and aims at reducing the GHG emissions by 37.5% before 2030.

In addition, following the European Green Deal, the French government introduced **"the national strategy for decarbonised hydrogen"** on September, 8 2020. This strategy set three objectives: a) installing enough electrolyzers to make a significant contribution to the decarbonation of the economy: the government aims at reaching a hydrogen production capacity of 6.5 GW by 2030; b) developing clean mobility, particularly for heavy vehicles, in order to save over 6 million tonnes of CO<sub>2</sub> by 2030: the government would like to develop territorial projects involving local authorities and industries in order to accelerate the deployment of hydrogen-powered professional mobility; and c) building an industrial sector in France that creates jobs and guarantees technological expertise. The government support will reach 7 billion euros and will focus on both supply and demand, supporting research to develop more efficient technologies.

## 2.3. Two Case Studies on biomasse

### BioTfuel

The BioTfuel project developed by Axens, CEA, IFP Énergies Nouvelles, Avril, ThyssenKrupp Industrial Solutions and TotalEnergies aims to develop an innovative process for the gasification of biomass into high quality biodiesel and biokerosene. The gasification allows to enlarge the spectrum of biomass usable for the production of biofuels by using lignocellulose (agricultural co-products, forest residues or specific biomass). This process can also be used to treat fossil feedstocks mixed with biomass, in particular, to take into account the seasonal nature of the resource. This project aims to develop and commercialize a complete process chain for the thermochemical production of advanced biodiesel and biokerosene. These high-quality fuels will be free of sulfur and aromatic compounds and can be used, alone or in blends, in all types of diesel and jet engines.



Fig. 12. Location BioTfuel

## Futurol

Launched in 2008, the Futurol™ project has been conducted with the support of 11 partners, covering the entire process, from the plant resource to the fuel tank: ARD, IFP Energies nouvelles, INRAE, Lesaffre, Office national des forêts (French National forestry Office), Tereos, Total, Vivescia, Crédit Agricole Nord Est Participations, CGB and Unigrains. The various steps in the process were successfully validated on a continuous pilot at Pomacle-Bazancourt (Marne, northern France) and an industrial demonstrator at Tereos' Bucy-le-Long site.



Fig. 13. Location Futurol R&D Teams

The Futurol project will develop a process to produce bioethanol by fermenting non-food lignocellulosic biomass. Many other products can be obtained from such process for fuel/energy and chemical applications alike. The originality of Futurol™ technology lies in its four-step implementation process: steam explosion of biomass, combined hydrolysis and fermentation, ethanol separation and in-situ enzyme production. One of its great strengths is its autonomy. Technological autonomy, first of all, thanks to the in situ production of the enzymes and the propagation of yeasts adapted to the raw materials treated. And also in terms of energy, since the technology enables total autonomy of the industrial site, and even energy exports.

A first industrial plant will be built by INA which will produce 55 000 tons (equivalent to 70 million liters of ethanol) of bioethanol using lignocellulosic raw materials such as agricultural waste and energy crops such as miscanthus.

In addition to advanced biofuels, processes such as BioTfuel or Futurol (a process for converting lignocellulosic residues into ethanol) also produce molecules that can be used in subsequent transformation processes to produce biobased chemical intermediates. For example, the ATOL process converts ethanol produced from lignocellulosic derivatives into bio-olefins. This type of combination amounts to establishing biorefineries that satisfy both the biofuel and chemical intermediate markets.

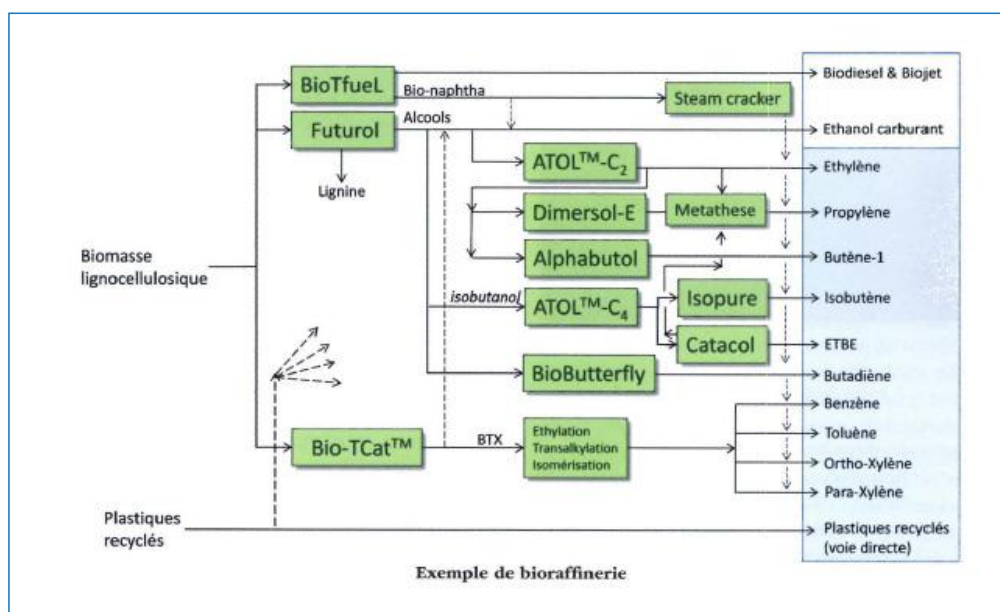


Fig. 14. Evolution of final energy consumption by source

## Table of Contents

---

1.	Introduction .....	335
2.	Energy perspectives 2030 - 2050 .....	338

## 1. Introduction

### National energy profile 2019

#### Total yearly consumption: final energy, electricity (TWh)

Year	Energy Consumption (TWh)	Electricity Consumption (TWh)	Elec/Energy (%)
1990	2 800	527	18.8
1995	2 713	516	19.0
2000	2 619	545	20.1
2005	2 694	589	21.8
2010	2 697	594	22.0
2015	2 569	574	22.3
2019	2 578	549	21.3

**Table 1.** Total yearly consumption: final energy, electricity

Data from IEA, Data & Statistics: <https://www.iea.org/data-and-statistics/data-tables?country=GERMANY&energy=Balances&year=2019> and <https://www.iea.org/data-and-statistics/data-browser?country=GERMANY&fuel=Energy%20consumption&indicator=TotElecCons>

Energy consumption in Germany decreased by 8% during the period from 1990 to 2019. This resulted from: a) improvements in energy efficiency; b) substitutions in the energy mix; and c) a decline in energy consumption in energy-intensive industrial sectors. The consumption-enhancing factors, such as population growth and mild weather, were significantly weaker than the consumption-reducing ones.

Concerning electricity, after an increase of around 44% between 1990 and 2010, consumption slightly decreased from 2010 to 2019. An increase in the electricity consumption / final energy consumption ratio could be observed during the period considered.

#### Per capita yearly final energy and electricity consumptions (MWh)

Year	Inhabitants (per million)	Energy Consumption (TWh)	Energy Consumption per person and per year (MWh)	Electricity Consumption (TWh)	Electricity Consumption per person and per year (MWh)
1990	79.0	2 800	35.5	527	6.7
1995	81.1	2 713	33.4	516	6.4
2000	81.4	2 619	32.2	545	6.7
2005	81.6	2 694	33.0	589	7.2
2010	80.8	2 697	33.4	594	7.3
2015	81.8	2 569	31.4	574	7.0
2019	83.5	2 578	30.9	549	6.6

**Table 2.** Per capita yearly final energy and electricity consumptions  
Data from IEA, Key World energy Statistics, Selected indicators.

Per capita energy consumption in Germany declined by 13%, during the period 1990–2019, while per capita electricity consumption remained static.

### Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>), total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)

Year	Total CO <sub>2</sub> Emissions (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions from electricity (MtCO <sub>2</sub> )	CO <sub>2</sub> emissions per capita
1990	940.0	342.7	11.8
1995	856.6	322.4	10.5
2000	812.3	311.9	10.0
2005	786.9	315.3	9.7
2010	758.9	300.1	9.5
2015	729.7	290.0	8.9
2019	644.1	209.5	7.8

**Table 3.** Total CO<sub>2</sub> emissions, from electricity production, and per capita by year

Tables are based and / or calculated from the following data

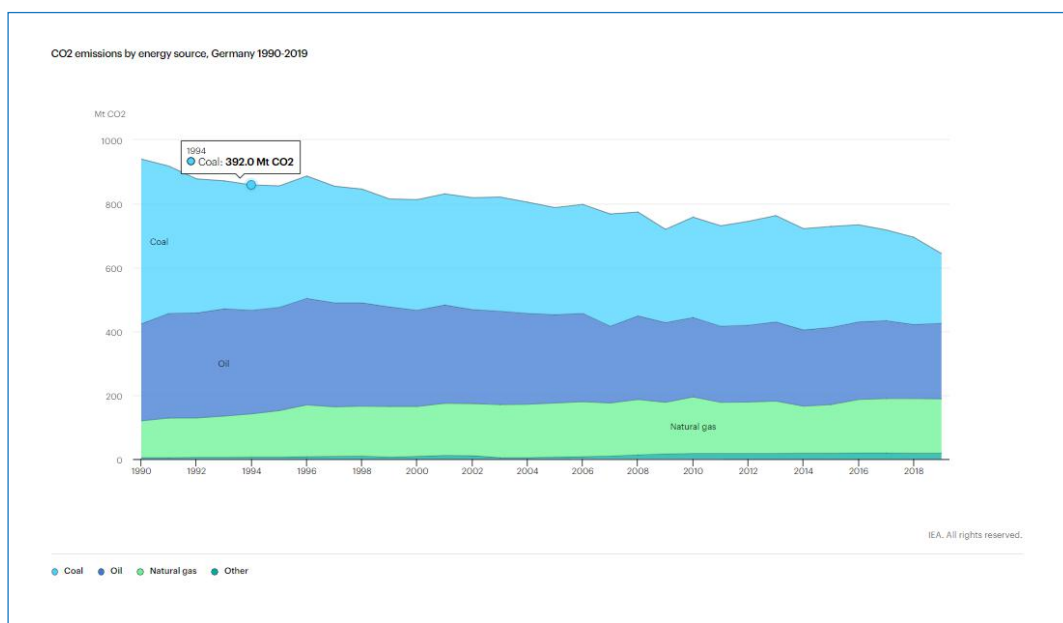
International Energy Agency - Data and statistics -Explore energy data by category, indicator, country or region

IEA (2021) Emission Factors ([https://www.iea.org/t\\_c/termsandconditions/](https://www.iea.org/t_c/termsandconditions/))

<https://www.worldometers.info/world-population/population-by-country/>

CO<sub>2</sub> emissions in Germany have fallen since 1990: from 940 million metric tonnes of CO<sub>2</sub> equivalents in 1990 to 644 million metric tonnes in 2019. Overall, this corresponds to a reduction of around 31.5%. CO<sub>2</sub> emissions per capita have also been dropping by around one third during the last 20 years. This is mainly due to increased emissions trading certificate prices and the expansion of renewable energies.

### CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)



**Fig. 1.** CO<sub>2</sub> emissions by fossil energy source

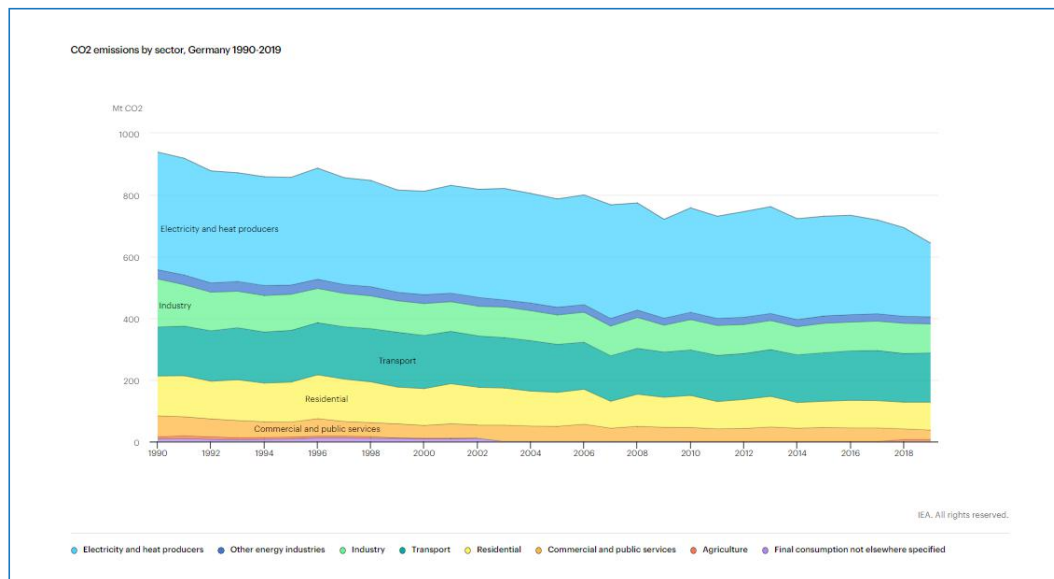
Data from IEA, Data & Statistics

<https://www.iea.org/data-and-statistics/data-browser?country=GERMANY&fuel=CO2%20emissions&indicator=CO2BySource>

During the period 1990-2019, CO<sub>2</sub> emissions from coal significantly decreased (from 514 Mt in 1990 to 218 Mt in 2019), which indicates a strong reduction in coal-fired power generation in Germany.

While the use of natural gas has increased by 47.8% during the period considered (from 115 Mt in 1990 to 170 Mt in 2019), the use of oil has fallen by almost one-third (from 301 Mt in 1990 to 237 Mt in 2019).

## CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)



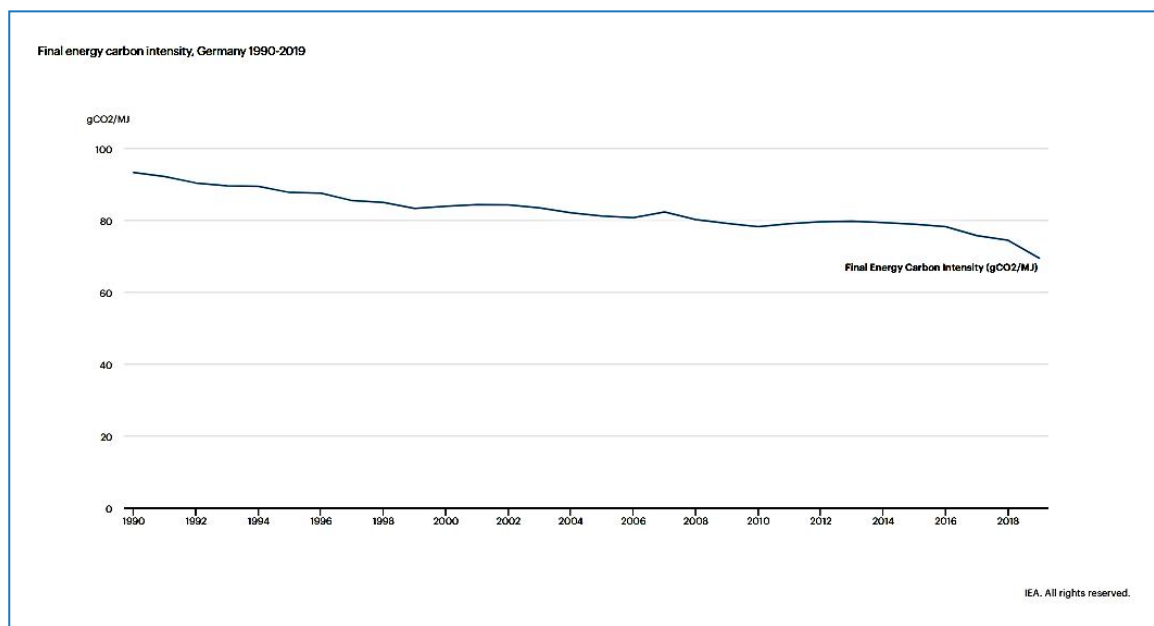
**Fig. 2.** CO<sub>2</sub> emissions by sector

Data from IEA, Data & Statistics

<https://www.iea.org/data-and-statistics/data-browser?country=GERMANY&fuel=CO2%20emissions&indicator=CO2BySector>

With the exception of the transport sector, in which CO<sub>2</sub> emissions remained unchanged, the amount of CO<sub>2</sub> emissions in all other sectors decreased during the period 1990–2019. The significant decline in emissions from the industrial sector is visible in this diagram.

## Final energy carbon intensity: gCO<sub>2</sub>/MJ and gCO<sub>2</sub>/kWh (1 Megajoule = 0.27778 Kilowatt hours)



**Fig. 3.** Final energy carbon intensity

Data from IEA, Data & Statistics <https://www.iea.org/data-and-statistics/data-browser?country=GERMANY&fuel=CO2%20emissions&indicator=FECI>

Between 1990 and 2019, emission intensity in Germany decreased by a good quarter (25.5%), falling from 93.2 gCO<sub>2</sub>/MJ to 69.4 gCO<sub>2</sub>/MJ. This development reflects the increased use of biofuels and the reduction of the shares of gas and coal in the German electricity mix.

### Electricity Carbon intensity: gCO<sub>2</sub>/kWh

The CO<sub>2</sub> intensity of electricity has always been low due to the important share of nuclear electricity generation capacity, and also the contribution of hydroelectricity. The values were: 108 g in 1990, 77 g in 2000, 50 g in 2020. This decrease was largely consequence of the phasing out of most of the coal plants and also to the increase of wind and solar electricity this last years.

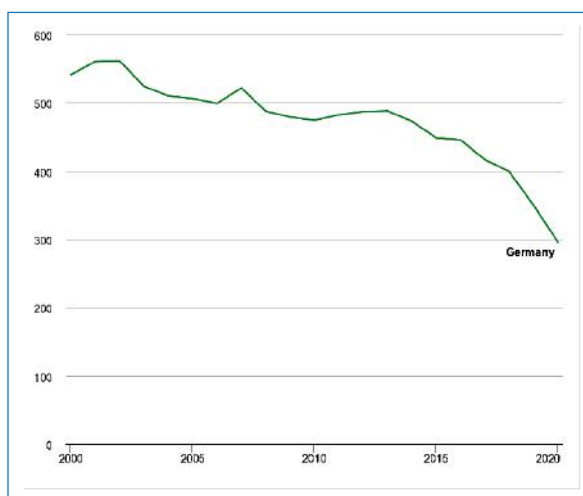


Fig. 4. Electricity Carbon intensity

<https://www.iea.org/data-and-statistics/charts/development-of-co2-emission-intensity-of-electricity-generation-in-selected-countries-2000-2020>

The CO<sub>2</sub> intensity of electricity generation in Germany fell from 541.6 gCO<sub>2</sub>/kWh to 295.8 gCO<sub>2</sub>/kWh between 2000 and 2020. The main factor that contributed to this development was the fact that more electricity was being generated from renewable energy sources and less from coal firing.

## 2. Energy perspectives 2030 - 2050

If possible, give the national perspectives for 2030 and 2050 or the roadmap to 2030 and 2050 if they exist.

*The following list of questions should serve as a guide for providing information on this topic. Please feel free to answer in a different manner if you like.*

**Does your country have national roadmaps regarding energy production and GHG emissions? What legal status do these documents have? What is their timeline?**

### EU level

EU regulations are binding and must immediately be applied by the Member States. Germany must observe and implement regulations adopted by the EU, and therefore our national climate policy is closely linked to European climate policy. Both the European Green Deal (EGD) and the newly presented 'Fit for 55' package under the EGD have a huge impact on our national targets and laws.

### European Green Deal

The Green Deal is a comprehensive growth strategy for a climate-neutral and resource-efficient economy. Its primary objective is to achieve EU-wide net zero emissions by 2050, which would make Europe the first climate-neutral continent in the world. On 11 December 2019, the Commission presented a Communication setting out its vision for the Green Deal and a comprehensive work programme to develop EU policies along these lines. The European Green Deal shows how sustainable transformation can succeed. It contains a range of different measures spanning climate action, nature conservation, biodiversity conservation and mobility and industrial policy to energy, agricultural and consumer protection policy.

The European Green Deal is also our lifeline out of the COVID-19 pandemic. One third of the EUR 1.8 trillion investments from the 'Next Generation EU' Recovery Plan and the EU's seven-year budget will finance the European Green Deal.

## Fit for the 55-package under the EGD

As part of the European Green Deal, with the European Climate Law, the EU has set itself a binding target of achieving climate neutrality by 2050. This requires current greenhouse gas emission levels to substantially drop in the next decades. As an intermediate step towards climate neutrality, the EU has raised its 2030 climate ambition, committing to cutting emissions by at least 55% by 2030, compared to 1990 levels. On 14 July 2021, the European Commission adopted a package of proposals to implement the increased ambition. The package contains legislative proposals to revise the entire EU 2030 climate and energy framework, including the legislation on effort sharing, land use and forestry, renewable energy, energy efficiency, emission standards for new cars and vans, and the Energy Taxation Directive. The Commission proposes to strengthen the emissions trading system (ETS), extend it to the maritime sector, and reduce over time the free allowances allocated to airlines. A proposed new emissions trading system for road transport and buildings should start in 2025, complemented by a new social climate fund with a financial envelope of EUR 72.2 billion to address its social impacts. New legislation is proposed on clean maritime and aviation fuels. To ensure the fair pricing of GHG emissions associated with imported goods, the Commission proposes a new carbon border adjustment mechanism.

## National level

### Climate Action Act

Germany's Climate Change Act first entered into force in December 2019. The purpose of this Act is to provide protection from the effects of worldwide climate change by ensuring the achievement of the national climate targets and compliance with the European targets.

An amended Climate Change Act 2021 was presented by the Federal Government on 12 May 2019. The new law brings forward the deadline for achieving climate neutrality by five years to 2045 and tightens the interim target for greenhouse gas emission reduction from 55% to 65% by 2030 compared to 1990. For 2040, a new interim target of 88% reduction applies. After the year 2050, negative greenhouse gas emissions are to be achieved (For details, see *Roadmap for the GHG emissions*, page 339).

### Energy Efficiency Roadmap

The Roadmap was launched on 18 December 2019, when the Federal Government adopted the cross-sectoral Energy Efficiency Strategy 2050. The stated aim of the Energy Efficiency Strategy 2050 at the time was for German primary energy consumption to fall by 30% by 2030 and by 50% by 2050 (from 2008)<sup>1</sup>. The target date for the completion of the dialogue process is autumn 2022.

The amendment to the Climate Change Act 2021 tightened climate regulations and enshrined in law the goal of achieving greenhouse gas neutrality by 2045. This meant a change to the timetable for the Energy Efficiency Roadmap. Even more ambitious energy efficiency targets are to be attained: by 2030, primary energy consumption is to fall by around 40% and it must be halved by 2045<sup>2</sup>.

### Roadmap for the energy mix

Germany's National Energy and Climate Plan, adopted on 10 June 2020, considers expanding renewable energies to 30% of gross final energy consumption by 2030<sup>3</sup>.

### Roadmap for the GHG emissions

In a ruling announced on 29 April 2021, the German Federal Constitutional Court delivered a ground breaking decision on national climate change legislation. Germany's Federal Court of Justice ruled that the country's 2019 Climate Change Act, which required that greenhouse gas emissions be gradually reduced by the target year 2030 by at least 55% relative to 1990 levels, was partly 'unconstitutional' because it shifted the climate burden of making painful reductions to future generations. The Court instructed the German legislator to revise the Federal Climate Change Act by the end of 2022.

<sup>1</sup> [https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/energieeffizienzstrategie-2050.pdf?\\_\\_blob=publicationFile&v=12](https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/energieeffizienzstrategie-2050.pdf?__blob=publicationFile&v=12)

<sup>2</sup> [https://www.bmwi-energiewende.de/EWD/Redaktion/EN/Newsletter/2021/06/en-newsletter\\_2021-06.html?\\_\\_act=renderPdf&\\_\\_iDocId=2720684](https://www.bmwi-energiewende.de/EWD/Redaktion/EN/Newsletter/2021/06/en-newsletter_2021-06.html?__act=renderPdf&__iDocId=2720684)

<sup>3</sup> [National Energy and Climate Plan](#), Page 11

On 24 June 2021, the Bundestag (Federal Parliament) adopted the reform of the Climate Change Act. With the amendment to the Climate Change Act, the German Federal Government intends to tighten climate regulations and enshrine in law the goal of achieving greenhouse gas neutrality by 2045.

The target for 2030 is to reduce emissions by 65% of 1990 levels by 2030<sup>4</sup>. This means that by the end of the decade, Germany is to reduce its greenhouse gas emissions by 65% of the 1990 levels.

The climate goals are reviewed through continuous monitoring. Every two years, the Council of Experts for Climate Matters will present a report of the goals achieved, as well as measures and trends. The first report is being prepared in 2022. If the targets are not met, the federal government will immediately adjust its approach.

For 2040 the reduction target is a minimum of 88%. Along the road to this goal, the Act lays down specific annual reduction targets during the 2030s. Germany is to become greenhouse gas neutral by 2045. This means that there must be a balance between greenhouse gas emissions and the removal of such gases. From 2050 onward, Germany aims to have a negative emissions balance, meaning that it would then remove more greenhouse gases using natural sinks than emit any.

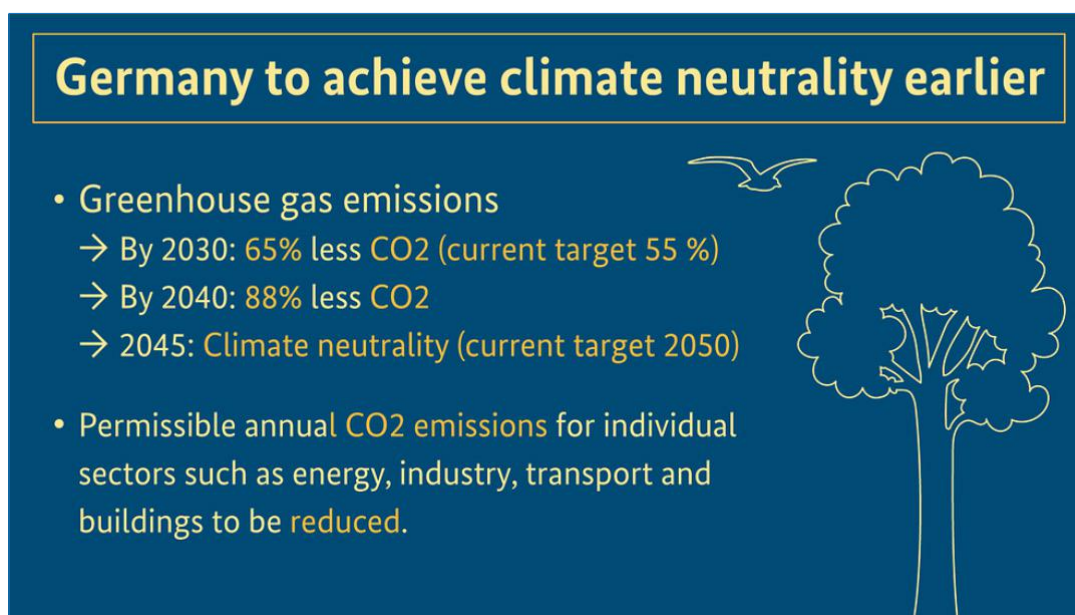


Fig. 5. Roadmap for achieving climate neutrality

With the amended Climate Change Act, the Federal Government does not only intend to provide for greater intergenerational justice. It will also put in place a more secure basis on which to plan. The road to climate neutrality is now set out in even more detail. Below is an overview of the milestones.

Cabinet decision of 12 May 2021: increase annual reduction targets per sector for the period 2023 to 2030 and enshrine the annual reduction targets for the period 2031 to 2040 in law.

2024: determine the annual reduction targets by sector for the period 2031 to 2040.

No later than 2032: determine the annual reduction targets for the period 2041 to 2045.

2034: determine the annual reduction goals by sector for the final phase leading up to greenhouse gas neutrality (2041 to 2045).

<sup>4</sup> <https://www.bundesregierung.de/breg-de/themen/klimaschutz/climate-change-act-2021-1936846>

## Roadmap for the electricity mix

Germany's electricity supply is becoming 'greener' every year. The share of renewables in electricity consumption has been steadily growing over the last few years – rising from around 6% in 2000 to around 38% in 2018. This means that the 35% target for 2020 was reached earlier than expected.

Wind and solar energy are the most important forms of renewables. Biomass and hydropower are also valuable building blocks in our energy system. The role of wind and solar energy is expected to strongly increase in the future.

The expansion of renewable energy remains one of the key pillars of the energy transition. The share of renewable energy is to be increased from its present level of around 32%, up to 40-45% in 2025, and to 65% in 2030 according to the coalition agreement. The next phase of the energy transition will focus on bringing about more competition, a continuous expansion with effective steering, restrictions on costs, stakeholder diversity and dovetailing with grid expansion.

## CO<sub>2</sub> emissions from electricity production

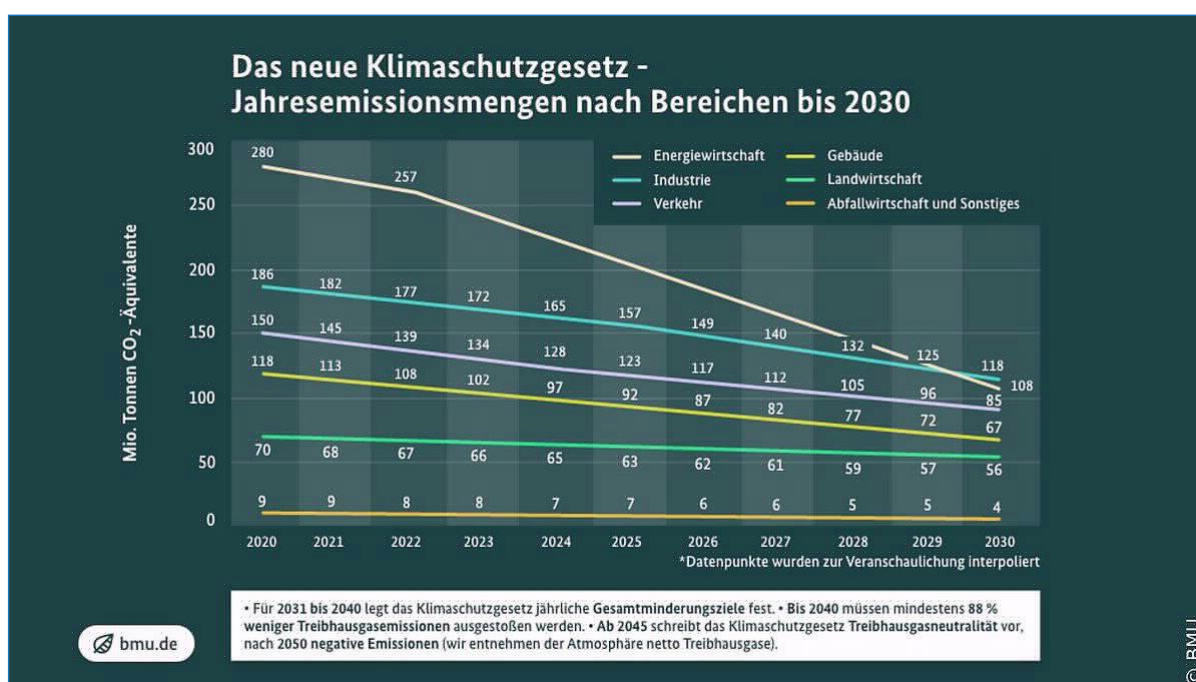


Fig. 6. CO<sub>2</sub> emissions from electricity generation

According to the Climate Change Act 2021, emissions in the energy sector are to be reduced to 108 million metric tons CO<sub>2</sub> by 2030<sup>5</sup>.

## Energy balance (energy sources to end-uses)

Total primary energy consumption 2020

In 2020, due to the COVID-19 pandemic, primary energy consumption in Germany amounted to a total of 11 784 petajoules (PJ) or 3 273 TWh or 402.1 million tonnes of coal equivalents (Mtce); compared to the previous year, this equals a decrease of 8.0%<sup>6</sup>.

<sup>5</sup> Federal Climate Change Act (Bundes-Klimaschutzgesetz), Annex 2

<sup>6</sup> AGEB Annual Report 2020: Energy Consumption in Germany Drops to Historic Low in 2020 Due to the Covid-19 Pandemic

**Primary Energy Consumption in Germany in 2019 and 2020 <sup>1)</sup>**

Energy Carrier	2019	2020	2019	2020	Changes in 2020 Compared to 2019			Proportions in %	
	Petajoules (PJ)		Million Tons of Coal Equivalents (Mtce)		PJ	Mtce	%	2019	2020
Mineral Oil	4,511	3,973	153.9	135.6	- 538	- 18.4	- 11.9	35.2	33.7
Natural Gas	3,214	3,136	109.7	107.0	- 78	- 2.7	- 2.4	25.1	26.6
Hard Coal	1,084	904	37.0	30.8	- 180	- 6.1	- 16.6	8.5	7.7
Lignite	1,164	956	39.7	32.6	- 207	- 7.1	- 17.8	9.1	8.1
Nuclear Energy	819	702	27.9	24.0	- 117	- 4.0	- 14.2	6.4	6.0
Renewable Energy	1,904	1,961	65.0	66.9	57	1.9	3.0	14.9	16.6
Electricity Exchange Balance	- 118	- 72	- 4.0	- 2.5	46	1.6	-	- 0.9	- 0.6
Other	228	224	7.8	7.6	- 4	- 0.1	- 1.8	1.8	1.9
<b>Total</b>	<b>12,805</b>	<b>11,784</b>	<b>436.9</b>	<b>402.1</b>	<b>- 1,021</b>	<b>- 34.8</b>	<b>- 8.0</b>	<b>100.0</b>	<b>100.0</b>

**Table 4.** Primary energy consumption in Germany in 2019 and 2020

[https://ag-energiebilanzen.de/wp-content/uploads/2021/12/ageb\\_jahresbericht2020\\_20210528\\_engl.pdf](https://ag-energiebilanzen.de/wp-content/uploads/2021/12/ageb_jahresbericht2020_20210528_engl.pdf)

The contributions of the diverse energy sources to the national energy mix shifted slightly in favour of renewables as well as natural gas in 2020 while total consumption volume turned out to be significantly smaller than it was in 2019.

Hard coal and lignite experienced further declines. Despite its slightly reduced share, mineral oil continued to be the most important energy source by far. A characteristic feature of the German energy supply continues to be its broad energy mix.

The level of energy consumption and its composition (energy mix) are also influenced by political and regulatory aspects. Significant for the medium-term to long-term development are, for example, the gradual phasing out from nuclear energy until the end of 2022, the scheduled exit from coal-fired power generation (by the end of 2038) as well as the continued undertaken promotion of renewable energy expansion.

### Primary energy production in Germany

Renewable energy carriers managed to significantly expand their position as the most important indigenous energy source ahead of lignite; their proportion in total domestic production now amounted to well above 57.7%, followed by lignite, which accounted for approximately 28.6% of domestic energy production. Both energy carriers continued to rank far ahead of natural gas and petroleum.

In 2020, taking primary energy consumption into account, the proportion of domestic production increased, namely from 27.5% in 2019 to now about 29.1% (see *Table 4*). This development was due to the fact that the COVID-19 pandemic caused primary energy consumption to decrease by 8% in 2020 – a much more significant decline than was recorded for the domestic production of primary energy carriers.

## Primary Energy Production in Germany in 2019 and 2020

	Production				Changes in 2020 Compared to 2019		Proportions	
	2019	2020	2019	2020			2019	2020
	Petajoules (PJ)		Million Tons of Coal Equivalents (Mtce)		PJ	%	%	
Mineral Oil	82	81	2.8	2.8	- 1	- 0.5	2.3	2.4
Natural Gas, Petroleum Gas	194	164	6.6	5.6	- 30	- 15.5	5.4	4.8
Hard Coal	0	0	0.0	0.0	0	0.0	0.0	0.0
Lignite	1,190	979	40.6	33.4	- 211	- 17.7	32.9	28.5
Renewable Energy	1,920	1,977	65.5	67.5	57	3.0	53.2	57.7
Other Energy Carriers	226	224	7.7	7.6	- 2	- 0.9	6.3	6.5
<b>Total</b>	<b>3,612</b>	<b>3,425</b>	<b>123.2</b>	<b>116.9</b>	<b>- 187</b>	<b>- 5.2</b>	<b>100.0</b>	<b>100.0</b>
For information purposes: Proportion of Primary Energy Consumption	-	-	-	-	-	-	27.5	29.1

Table 5. Primary energy production in Germany in 2019 and 2020

[https://ag-energiebilanzen.de/wp-content/uploads/2021/12/ageb\\_jahresbericht2020\\_20210528\\_engl.pdf](https://ag-energiebilanzen.de/wp-content/uploads/2021/12/ageb_jahresbericht2020_20210528_engl.pdf)

## Dependence on energy imports

Germany is a considerable net importer of virtually all fossil fuels (i. e. hard coals, mineral oil, and natural gas). In 2019, domestic primary energy consumption was covered by imports which amounted to 98% for mineral oil and 94% for natural gas. 100% of hard coals were sourced from imports. In contrast, 100% of lignite had been made available from indigenous resources, and renewables also came almost entirely from domestic production. All told, nearly 72% of the German energy supply was dependent on imports in 2019. This situation remained basically unchanged in 2020: Germany's dependence on imports was estimated to still amount to more than 71% then.

## Table of Contents

---

<b>1.</b>	<b>National energy profile 2019</b>	345
<b>2.</b>	<b>Energy perspectives 2030 - 2050</b>	347
<b>3.</b>	<b>Building sector</b>	351
3.1.	Existing buildings	351
3.2.	New buildings	353
<b>4.</b>	<b>Industry</b>	354

## 1. National energy profile 2019

### Total yearly consumption: final energy, electricity (TWh)

Year	Energy Consumption (TWh)	Electricity Consumption (TWh)	Elec/Energy (%)
1990	754.8	101.7	13.5
1995	1 217.5	175.0	14.4
2000	1 478.2	277.7	18.8
2005	1 633.5	373.8	22.9
2010	1 833.9	481.5	26.5
2015	2 014.5	534.7	26.5
2019	2 115.8	562.5	26.6

**Table 1.** Energy and electricity consumption

<https://www.iea.org/data-and-statistics/data-tables?country=KOREA&energy=Balances&year=2019>

and: <https://www.iea.org/data-and-statistics/data-browser/?country=KOREA&fuel=Energy%20consumption&indicator=TotElecCons>

Energy consumption increased about 1.8 times in the last 30 years, and electricity consumption increased about 4.5 times. Therefore, the ratio of electric energy consumption to total energy consumption has doubled from 13.5% in 1990 to 26.6% in 2019. This is a significant increase in energy use, and even more so in electricity, considering that the population has increased by only 20%.

### Per capita yearly final energy and electricity consumptions (MWh)

Year	MWh/year	MWh
1990	17.6	2.4
1995	26.9	3.9
2000	31.2	5.9
2005	33.5	7.7
2010	37.0	9.7
2015	39.7	10.5
2019	41.3	11.0

**Table 2.** Per capita final energy and electricity consumption

### Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>), total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)

Year	Total CO <sub>2</sub> Emissions (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions from electricity (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions per capita
1990	231.8	60.7	5.4
1995	357.3	90.1	7.9
2000	431.9	172.6	9.2
2005	457.7	206.8	9.5
2010	550.9	195.3	11.1
2015	582.1	155.3	11.4
2019	585.7	141.3	11.3

**Table 3.** CO<sub>2</sub> emissions from energy, electricity, and per capita

Total CO<sub>2</sub> emissions from energy production and consumption also more than doubled during this period. In the case of carbon dioxide emissions from fossil energy sources, it was mainly the use of coal that produced the increases. In addition, CO<sub>2</sub> emissions from the electricity and heat production sector accounted for the most significant proportion, which can be related to the increase in electricity consumption. Total CO<sub>2</sub> emissions from all the sectors in Korea peaked at 727.6 MtCO<sub>2</sub> in 2018, and Korea submitted the NDC target of 40% reduction from the peak amount at the COP26 meeting in Glasgow in 2021.

### CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)

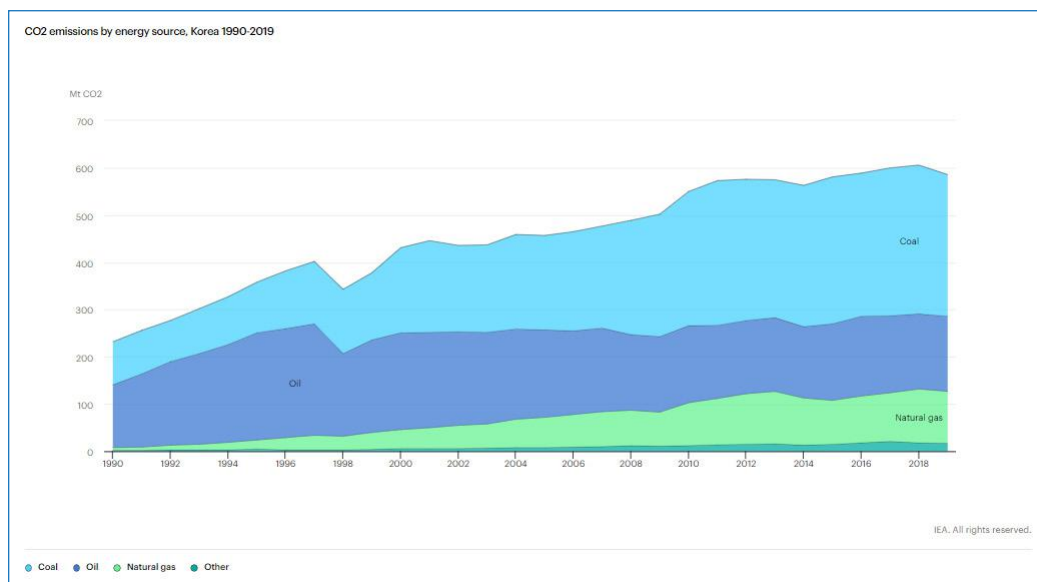


Fig. 1. CO<sub>2</sub> emissions by fossil energy source

<https://www.iea.org/data-and-statistics/data-browser?country=KOREA&fuel=CO2%20emissions&indicator=CO2BySource>

### CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)

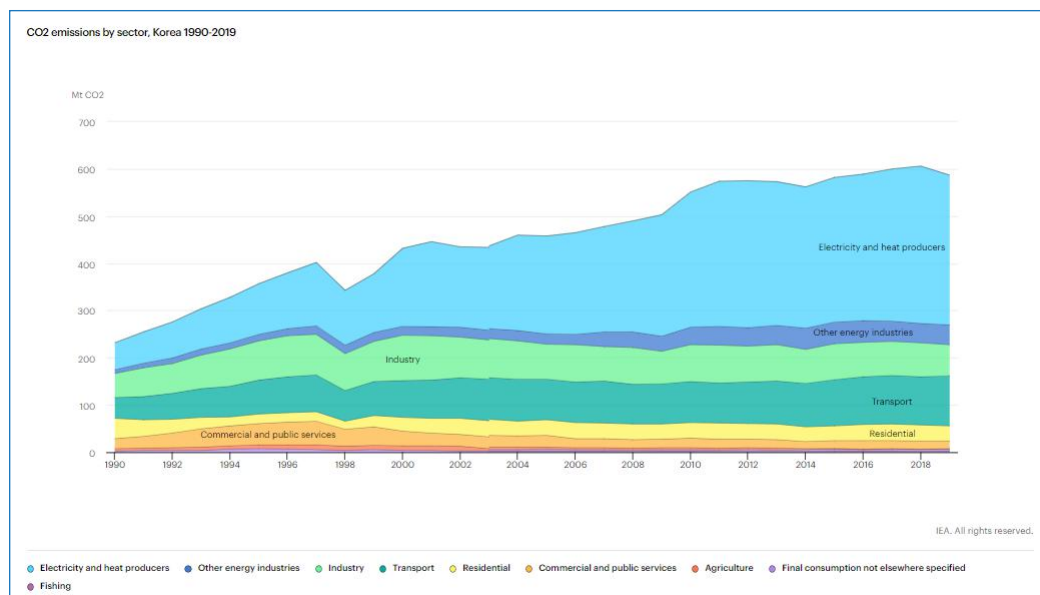
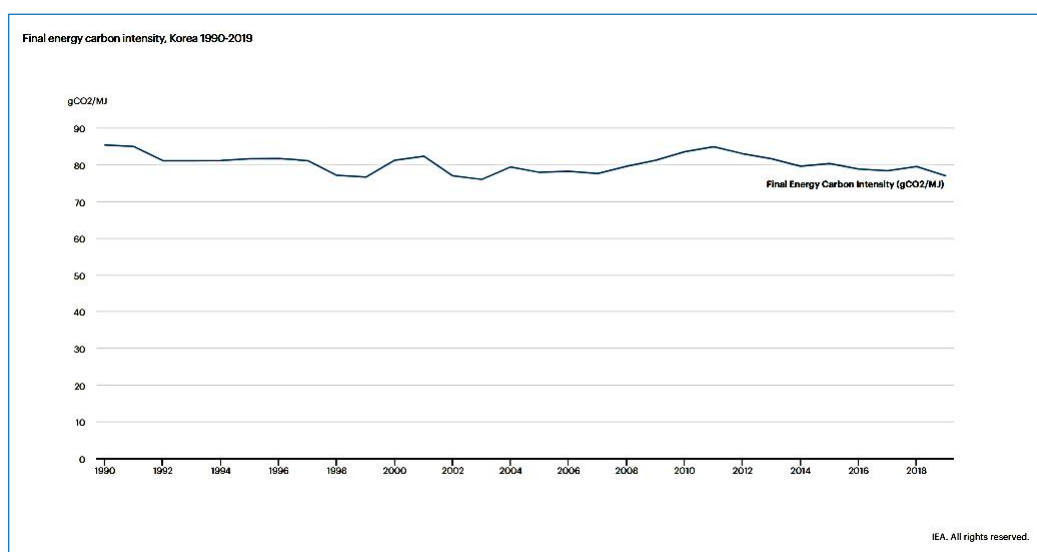


Fig. 2. CO<sub>2</sub> emissions by sector

<https://www.iea.org/data-and-statistics/data-browser?country=KOREA&fuel=CO2%20emissions&indicator=CO2BySector>

## Final energy carbon intensity: gCO<sub>2</sub>/MJ and gCO<sub>2</sub>/kWh (1 Megajoule = 0.27778 kilowatt hours)



**Fig. 3.** Final energy carbon intensity

<https://www.iea.org/data-and-statistics/data-browser?country=KOREA&fuel=CO2%20emissions&indicator=FECI>

## Electricity Carbon intensity: gCO<sub>2</sub>/kWh

The CO<sub>2</sub> content of electricity in 2019 was 515 gCO<sub>2</sub>/kWh with a large use of coal (IEA Emissions factors)

## 2. Energy perspectives 2030 - 2050

If possible, give the national perspectives for 2030 and 2050 or the roadmap to 2030 and 2050 if they exist.

### Does your country have national roadmaps regarding energy production and GHG emissions?

#### What legal status do these documents have? What is their timeline?

In October 2021, The Presidential Committee on Carbon Neutrality announced the '2050 Carbon Neutrality Scenario', consisting of two roadmaps for the net-zero emission goal by 2050.

The first scenario aims to shut down all electric power plants using coal and LNG for achieving net-zero emissions in the power sector. The second road map also aims to cease coal power generation but keep LNG as a flexible power source. In this case, the plan seeks to boost carbon capture, utilization, and storage (CCUS) and direct air capture (DAC) capabilities.

As part of its broader aim to realize carbon neutrality by 2050, the Korean Government recently suggested the 2030 NDC (Nationally Determined Contribution) target with the reduction in greenhouse gas emissions by 40 per cent against the national maximum output level in 2018. It was officially introduced to the international community at the 26<sup>th</sup> United Nations Climate Change Conference (COP26) in November 2021, and this governmental plan will be submitted to the UN in December 2021 accordingly. Prior to determining the NDC, the Korean parliament passed the Basic Carbon-neutral Act in October 2021 and set the emission reduction target to be at a minimum 35% or more.

## Roadmap for the energy mix



Fig. 4. Energy Mix (Mtoe)

\*RE includes solar thermal, geothermal, hydrothermal, and biomass, while solar PV and wind energy for power generation are included in the Power section.

By 2050, the use of coal, oil, and LNG, which emit GHG, is anticipated to decrease significantly, whereas the demand for power and renewable energy as well as hydrogen is expected to increase considerably.

## Roadmap for the GHG emissions (country, total)

According to the national roadmap, GHG emissions in 2030 will be reduced by 40% compared to that in 2018, and net-zero GHG emissions will be accomplished by 2050. In order to meet these targets, expanding the use of renewable power, green hydrogen, and electric vehicles will not be enough and the field application of various technologies to capture and store carbon dioxide (e.g. CCUS, DAC) will be needed. The CO<sub>2</sub> reduction and carbon sink outside Korea such as forests and the oceans should also be much enhanced, while avoiding further ocean acidification.

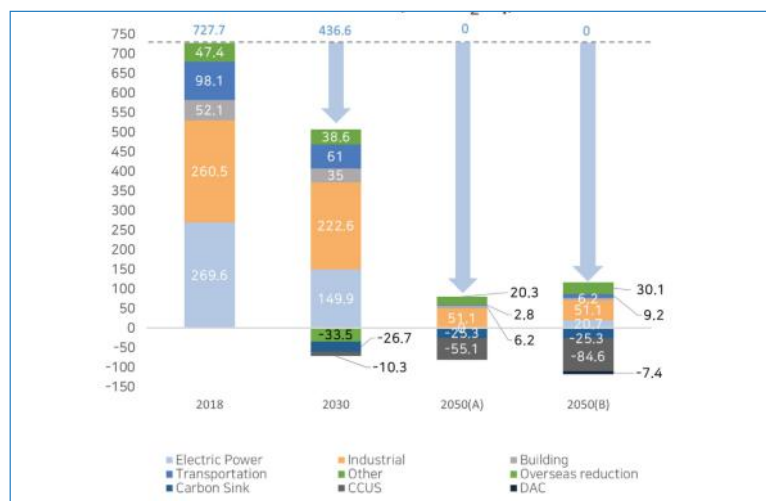


Fig. 5. GHG Emissions (MtCO<sub>2eq</sub>)

	Electric power	Industrial	Building	Transportation	Other*	Overseas reduction	Carbon Sink	CCUS	DAC	Net Total (MtCO <sub>2e</sub> )
2018	269.6	260.5	52.1	98.1	47.4					727.7
2030	149.9	222.6	35.0	61.0	38.6	-33.5	-26.7	-10.3		436.6
2050(A)	0.0	51.1	6.2	2.8	20.3	0.0	-25.3	-55.1		0.0
2050(B)	20.7	51.1	6.2	9.2	30.1	0.0	-25.3	-84.6	-7.4	0.0

Table 4. GHG reduction from 2018 to 2050 (Roadmap)

\*Other includes waste, farming (agriculture, livestock farming and fisheries), and hydrogen.

## Roadmap for the electricity mix

To achieve carbon neutrality, renewable energy that does not emit GHG —solar and wind power in particular — should be the main source of energy. Under this scenario, energy use in industrial, transport, cooling and heating sectors should be electrified as much as possible. Therefore, it is assumed that electricity demand in 2050 will be more than double the amount of electricity consumption in 2018.

Electricity generated from fossil fuels such as coal and LNG must be minimized or zero. Until 2030, coal power plants will be gradually shut down, and renewable electricity will be substantially expanded. In addition, carbon-free fuels such as ammonia will be newly introduced to the electricity mix. It is assumed that coal power plants will be completely shut down before 2050 regardless of which of the two scenario plans in 1.2.2. is chosen. LNG will be completely stopped under the plan A, or will remain as a flexible power source under the plan B. As an alternative to coal and LNG, renewable energy, such as solar and wind power, is expected to hold the highest proportion in the power mix by 2050, where in plan A it is expected to increase to 70.8% and in plan B to 60.9%.

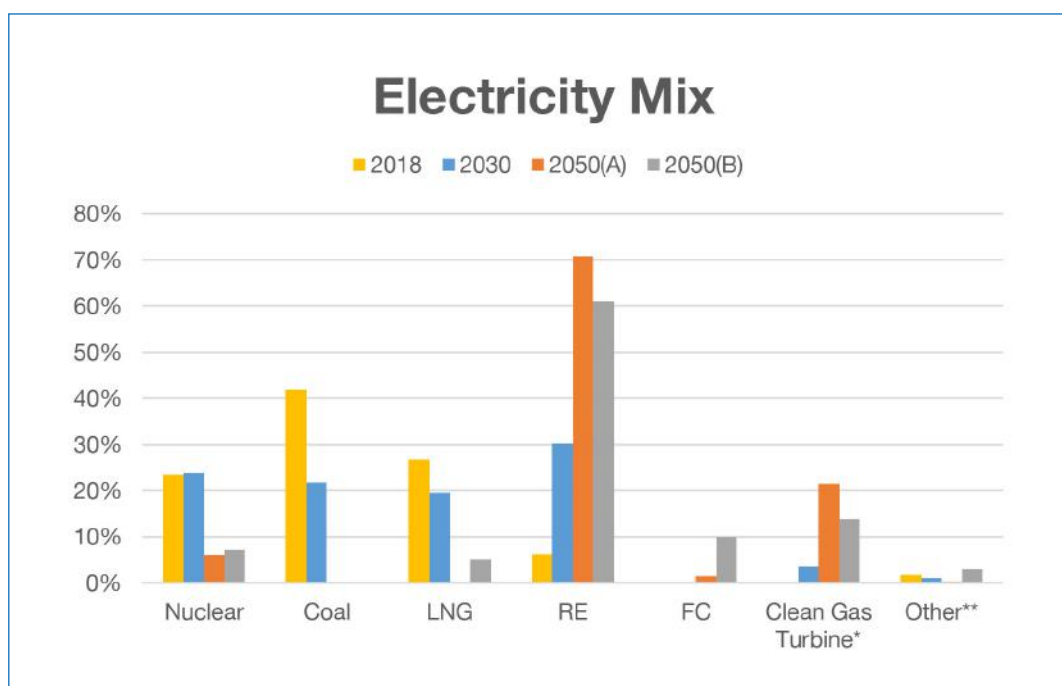


Fig. 6. Electricity Mix 2018 to 2050

		Nuclear	Coal	LNG	RE	FC	Clean Gas Turbine*	Other**	Total (TWh)%
<b>2018</b>		133.5	239.0	152.9	35.6			9.6	570.7
<b>2030</b>		23.4%	41.9%	26.8%	6.2%			1.7%	100.0%
		146.4	133.2	119.5	185.2		22.1	6.0	612.4
		23.9%	21.8%	19.5%	30.2%		3.6%	1.0	100.0%
<b>2050</b>	<b>A</b>	76.9	0.0	0.0	889.8	17.1	270.0	3.9	1 257.7
		6.1%	0.0	0.0	70.7%	1.4%	21.5%	0.3%	100.0%
	<b>B</b>	86.9	0.0	61.0	736.0	121.4	166.5	37.0	1 208.8
		7.2%	0.0	5.0%	60.9%	10.0%	13.8%	3.0%	100.0%

Table 5. Roadmap to 2050 for electricity production with in scenario A no coal and LNG based power generation and in scenario B keeping some power generation running on LNG

\*Power generation by clean fuel including ammonia.

\*\*Others include electricity supplied from pumped-hydro power generation (2030), north-east Asia super grid, and blast furnace gas (2050).

### CO<sub>2</sub> emissions from electricity production

Depending on the electricity mix, GHG emissions from coal and LNG will still exist by 2030, but by 2050, such emissions will totally disappear (plan A) or continue in only very small amounts (plan B) by 2050.

Energy balance (energy sources to end-uses)

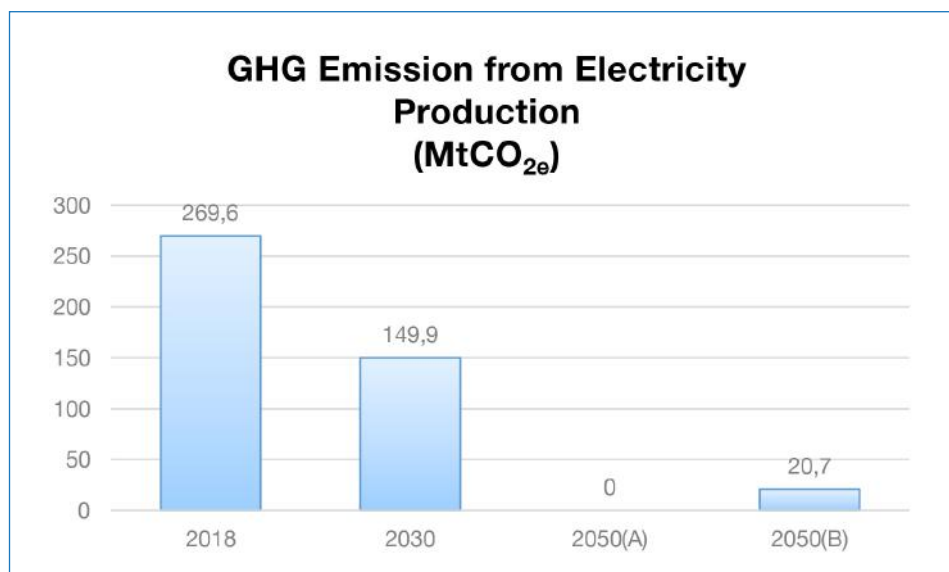


Fig. 7. GHG Emissions from Electricity Generation

By 2050, energy demand is anticipated to decrease by 5.0% compared to 2018. While on the one hand energy demand is expected to decrease mainly in buildings and transportation, on the other hand, it is expected to increase in the use of new technologies such as CCUS and hydrogen.

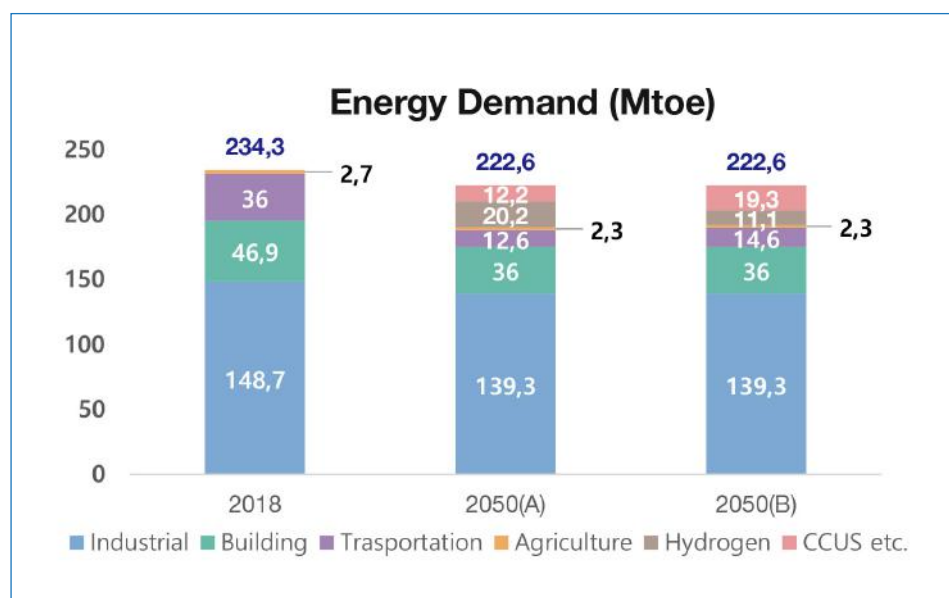


Fig. 8. Energy demand by sector in 2018 and 2050, including hydrogen production and CCUS (1 Mtoe = 11.63 TWh, eg. 234.3 Mtoe = 2720 TWh)

### 3. Building sector

#### 3.1. Existing buildings

##### Energy balance 2019 (energy sources to end-uses)

The building sector consumes most energy in the form of electricity (45%), followed by city gas (31%). More than 80% of the energy used in the building sector is supplied by fossil fuels.

Sector/ Energy	Coal	Petroleum	LNG	City Gas	Hydro	Nuclear	Electricity	Heat	Renew- ables & Others1*	Total
1 000 toe										
Residential	306	3 051	-	10 479	-	-	6 059	2 277	447	22 619
Commercial	-	1 773	-	3 630	-	-	11 628	306	132	17 469
Public	-	1 276	-	78	-	-	2 766	63	1 205	5 388
<b>Total</b>	<b>306</b>	<b>6 100</b>	<b>-</b>	<b>14 187</b>	<b>-</b>	<b>-</b>	<b>20 453</b>	<b>2 646</b>	<b>1 784</b>	<b>45 476</b>

**Table 6.** Energy consumption of residential, commercial, and public buildings

\*Source: Energy Statistics of 2020 published for 2019 consumption (unit 1 000 toe), Electricity 20 453 toe = 238 TWh

##### Energy partition between single houses, apartment buildings and office buildings

Apartment buildings account for the highest proportion of households in Korea, consuming about 49% of energy, while single houses consume about 35% of energy.

Residential Buildings						
Residential Total	Detached dwelling	Apartment	Row house	Apartment unit in a private house	House within Commercial Building	Commercial Building and Public
unit: 1 000 toe						
20 780	7 354	10 125	1 435	1 645	221	19 828

**Table 7.** Energy consumption by category of residential buildings, and commercial and public buildings

\*Source: Energy Consumption Survey of 2017 published for 2016 consumption that is the latest official statistics. 2021 Survey is not yet published.

##### Which systems are mostly used for heating?

For residential heating, city gas accounts for the highest proportion, followed by district heating. Commercial buildings have the highest percentage of electric heating mainly due to the use of electric heat pumps (EHP), followed by city gas heating.

Heating System and Energy Source for Heating		Residential*		Commercial and Public	
		Total Household Energy Consumption by Heating System Type		Heating and Hot Water	
		Tcal	%	Tcal	%
District Heating (Hot Water)		28 984	13.9	2 127	3.6
Boiler	City Gas	137 103	66.0	18 076	30.4
	Oil	24 253	11.6	4 720	7.9
	LPG	3 675	1.8	2 345	3.9
	Briquette	4 960	2.4	1 328	2.2
	Midnight Electricity	6 556	3.1	-	-
Heating by Electricity		600	0.3	30 238	50.9
Renewables and Others		1 667	0.8	615	1.0
<b>Total</b>		<b>207 798</b>	<b>100.0</b>	<b>59 449</b>	<b>100.0</b>

**Table 8.** Types of Energy consumption in Residential, commercial and public buildings (1 Tcal = 1.163 GWh)

\* Estimated percentage from total household energy consumption by heating system type using Energy Consumption Survey of 2017 that is the latest official statistics (2021 survey is not yet published).

### Which systems are mostly used for cooling? (local systems, cooling networks...)

The share of energy use for cooling in commercial buildings is 24%, and 87% of cooling is done by electric cooling. The share of energy use for cooling in residential houses is however very low. The major reason for this is that the household electricity bill is calculated based on the progressive pricing system. The household electricity progressive rating system has a great impact on reducing electricity consumption in residential houses.

Cooling System and Energy Source for Cooling		Residential*	Commercial and Public Building	
			Cooling Energy Consumption	
			Tcal	%
District Cooling		-	252	0.5
Absorption Chiller	City Gas		5 911	12.2
	LPG		40	0.1
Cooling by Electricity			42 207	87.2
Renewables and Others			3	0.006
Total			48 413	100.0

**Table 9.** Energy consumption in Residential, commercial and public buildings (1 Tcal = 1.163 GWh)

\*There are no official statistical data on residential energy use for cooling. Air-conditioning in a household uses primarily electricity. Energy use for cooling is estimated to account for about 10% of residential heating energy consumption.

### What are the main choices of the national policy – if there is one – to reduce the emissions from the existing stock of buildings? To make this reduction affordable?

#### From a technological point of view? (Insulation, heat pumps, low CO<sub>2</sub> district network, geothermal systems, local PV production, etc.).

Insulation (especially for windows) for a short-term strategy, heat pumps with green electricity (including local PV production) for a long-term strategy

#### From a regulatory point of view? Through land ownership regulations?

From 2020, zero-energy buildings became compulsory for all new public buildings, and private new buildings will also become zero-energy compulsory from 2025 onwards. There are some subsidy support systems for existing buildings but currently with no compulsory regulations. In the future, however, it is expected that policies based on the regulatory framework will be inevitable even for existing buildings. A green remodelling mandate for public buildings is being prepared.

#### Through subsidies, different financial mechanisms? Which are the priorities: reducing CO<sub>2</sub> or energy; better inclusivity.

Although some energy efficiency remodelling of existing buildings is being implemented with the aid of the national budget, a market-based carbon reduction mechanism in which all buildings participate is required for the carbon neutrality in the future. So far, mainly energy-based subsidies have been provided, but it is expected that CO<sub>2</sub>-based subsidies will also be introduced in the near future.

#### Replacing parts of the existing stock of buildings?

Up to 30% of new construction is indeed reconstruction or redevelopment, thus some of the existing stock of buildings is already being automatically improved. However, as carbon neutrality requires renovation of all the stocks of buildings in Korea, a new strategy is required.

#### Is there a specific roadmap for this subject?

According to the 2050 Carbon-neutral Scenario of Korea, due to improved energy efficiency in buildings and the supply of highly efficient equipment, energy demand in the building sector will decrease by 23% compared to that in 2018. As a result, fossil fuel consumption would be reduced from 47% in 2018 to 8% in 2050, and electricity and renewables would cover more than 84% of the total energy demand in 2050. Under these premises, the annual GHG emissions from the building sector in 2050 are expected to be reduced by 88.1%

compared to that in 2018. To this end, it is necessary to improve the energy intensities for cooling and heating by more than 30% by 2050 compared to those in 2018. This will be realised through 100% implementation of net-zero energy for newly constructed buildings and green remodelling for existing buildings. Furthermore, scaling up the deployment of highly efficient home/office appliances and lighting equipment and smart energy management systems for the building sector through HEMS and BEMS are expected to become effective mitigation strategies.

**Is there some roadmap for making existing cities more sustainable?**

Various urban regeneration projects are being implemented. However, a roadmap for decarbonizing the city's energy system or at least into a more sustainable system has not yet been established.

**Are there some case studies or best practices you would like to share?**

Korea has a national data platform that tracks the energy consumption of all the buildings nationwide on a monthly basis. This system was developed based on the billing information of the energy supplier. In the future, this platform will be used to support and manage the carbon neutrality of individual buildings in Korea.

**3.2. New buildings**

**Does your country have a national policy regarding new buildings?**

**If yes, what are the priorities? (For housing and for office buildings)**

Since the implementation of insulation standards in 1978, Korea developed an energy-efficient design standard that is applied to new buildings (except private housing/homes) for all uses and has been continuously strengthened. By 2025, the net-zero-energy building standard will become mandatory for new buildings/homes in the private sector as well. In the case of a residential house, the efficiency of energy for heating is emphasized, while for office buildings, efficiency improvement in air conditioning and lighting is relatively more important. Regarding the energy design standards for buildings, different weights on different energy-saving items are set for each destination/use of a building.

**Are some technologies prioritised, in particular for heating and cooling?**

**At the building level? At the infrastructure level?**

**(developing district networks, prohibiting connection to the gas network)**

From a building perspective, it is most important that insulation and airtightness are well designed and constructed. For future new buildings, it will be more important to improve the acceptability of renewable energy systems than to install such systems right away. From an energy supply point of view in the building sector, electricity use was curbed, and priority was given to gas and local heat sources. However, in order to meet carbon neutrality, all fossil fuels must be phased out and replaced by green electricity.

**How are they supported? Through regulations? Subsidies?**

Early legislation was implemented based on obligatory measures. Incentives were provided to induce buildings to improve their performance beyond the statutory level. A characteristic of Korea's incentive measures is that it uses a method of easing legal regulations, such as raising the floor area ratio (FAR), rather than direct support through subsidies.

**Are there some recommendations and regulations for sustainable districts and cities?**

---

**Are there some case studies or best practices you would like to share?**

As mentioned in the previous question, it is suggested to use non-financial incentives. And in the process of continuous regulatory upgrade, it is important to maintain close communication with the building-related industry.

## 4. Industry

Please choose three or four industries that are important for your country in the following list:

- Steel industry (including mining),
- Cement industry,
- Chemical industry (Petro-chemistry),

For each of these industries:

**What is the energy balance (energy sources used)?**

**And the GHG intensity, compared to other countries?**

Steel, Petro-chemistry and Cement are placed as top 3 carbon emission industries in Korea, and their emission accounts for ~70% of total industry sector's emission in Korea. They are not only energy intensive but also their main inputs contain carbon. Thus, it is a huge challenge to reduce carbon emissions from these sectors.

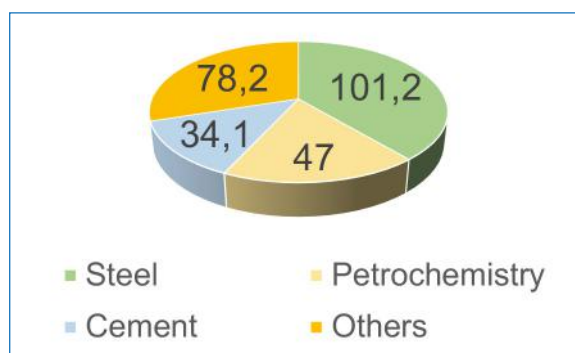
**Steel:** In 2018, Steel industry emitted 101.2 million metric tons of CO<sub>2</sub>, of which 95.3 million tons are direct emissions and 5.9 million tons are process emissions. 29 906 thousand toe energy were used in steel production. Coal is the main energy source with 25 182 thousand toe, which is used as a reducing agent to remove oxygen from the iron ores. The steel industry's GHG emission intensity is 4 909 tons CO<sub>2</sub> per billion KRW value-added production.

**Petro-chemistry:** The total amount of Petro-chemistry's CO<sub>2</sub> emissions and energy use was 47 million tons and 56 385 thousand toe, respectively in 2008. 98% of their emissions came from direct emissions; using petroleum-based naphtha as a main input and fossil fuel for making about 800 °C heat in NCC (Naphtha Cracking Center). For this reason, their energy consumption is concentrated on oil. Carbon intensity of petro-chemistry is 1 377 ton per billion Korean Won (KRW) value-added production.

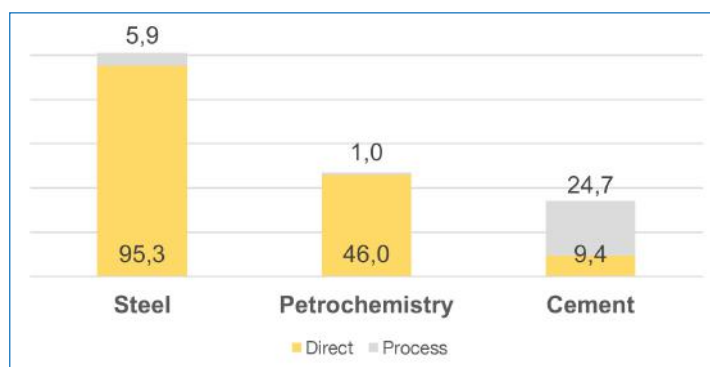
**Cement:** 34.1 million tons of CO<sub>2</sub> is emitted from the Cement industry. About 1400 °C of heat is needed to remove carbon from limestones, and in that process, CO<sub>2</sub> is emitted. Moreover, the heat is being supplied by burning huge amounts of bitumi-nous coal. This is why the cement industry has both large direct and process emission levels.

1 000 toe	Steel	Petro-chemistry	Cement
Coal	25 182	219	2 196
Oil	68	46 582	138
LNG	1 659	4 226	151
Electricity	2 997	5 359	582
Total	29 906	56 385	3 067

**Table 10.** Energy Usage of the Top 3 GHG Emission Industries in Korea  
Data: Internal data of KIET



**Fig. 9.** GHG Emissions of the industrial sector as a whole and the share due to Steel, Cement, and the Petrochemical Industry  
Data: Internal data of KIET



**Fig. 10.** GHG Emissions of Steel, Petrochemistry and Cement in 2018 (million tons CO<sub>2e</sub>)  
Data: Internal data of KIET

	Steel	Petro-chemistry	Cement
GHG Intensity (ton/billion KRW value-added)	4 909	1 377	25 658

**Table 11.** Energy Usage of Top 3 GHG Emission Industries in 2018  
Data: Internal data of KIET 2015 price-based real value-added production

## Are the best available low carbon technologies used/considered?

### If not, is it an economic problem? A matter of regulation? Or some social issues?

**Steel:** Despite many current technical obstacles, hydrogen-reduction-based steel making is considered as the best method to obtain the most eco-friendly steel making. Since the major emission source comes from using carbon-based reduction processes, the key is to find an alternative technology with noncarbon-related reduction, and hydrogen is in the spotlight as one of the best alternatives. Thus, global steel manufacturing companies are putting their resources into developing this alternative steel-making technology. Korea's steel industry is also making every effort to develop and commercialize the technology and aims to achieve net-zero direct emissions by 2050.

**Petro-chemistry:** Substituting petroleum-based naphtha with bio-based material is the first major approach for emission reduction while replacing fossil-oil based Naphtha Cracking Centers (NCC) with electric-powered facilities is another major one. The petrochemical industry is characterized by using crude oil as both its main fuel and raw material. Hence, it is indispensable in a net-zero world to decrease CO<sub>2</sub> emissions by introducing non-carbon input. Korea's petrochemical industry has a plan that by 2050, over half of the total amount of traditional naphtha will be replaced with bio-based raw materials, and electric furnaces will be introduced to minimize carbon emissions.

**Cement:** For reducing CO<sub>2</sub> emissions, changing the main heat source and increasing the use of non-carbonate materials are key for the cement industry. Korea's cement industry is trying to replace coal with combustible wastes, and its share in total heat sources will be minimised until 2050. The remaining part of the heat sources will also be entirely replaced with eco-friendly sources such as biomass and hydrogen. In addition, the use of limestone is going to be minimised until 2050 by expanding the share of non-carbonate materials like slag and ash.

## Is there a roadmap to decrease GHG emissions for 2030 - 2050

### If yes, what are the intermediary steps?

According to 2030 NDC and 2050 Carbon-neutral Scenario of the Korean government, the annual GHG emission of the industry sector in 2030 and 2050 is planned to be reduced by 14.5% and 80.4%, respectively compared to those in 2018. According to these plans, the steel industry will reduce its emission by 2.3% by 2030 and 95% by 2050. The petrochemical industry's reduction rates of annual greenhouse gas emissions in 2030 and 2050 are 20.2% and 73% compared to those in 2018. Finally, the cement industry has targeted to lower its emissions by 12% in 2030 and 53% in 2050.



Fig. 11. GHG Emission Reduction Roadmap of the Industry Section (Million ton CO<sub>2e</sub>)  
Data: Korea 2050 Carbon-Neutral Scenario and 2030 NDC

**Is the implementation of low-carbon technologies helped by the government? For refurbishing or replacing equipment? How are public authorities pushing the transformation? Through benchmarking? Audits?**

The Korean government allocated 11.9 trillion Korean Won (KRW) in 2022 as a budget for supporting the carbon-neutral transition. This budget includes support for the development and distribution of innovative carbon emission reduction technologies such as hydrogen-reduction-based steel making. Furthermore, the government expresses its intention to support the entire R&D streams from basic research to the establishment of pilot facilities in the long run. Recently, the Korean government legislated the 2030 NDC goal which targets 40% reduction of the annual GHG emission level compared to that in 2018. However, there are not sufficient measures or incentives to force companies to bear the cost of emission reduction. Instead, Korea's 2030 NDC is regarded as a benchmark, and the Korean government is trying to establish diverse incentive-based policies and financial support measures for companies to voluntarily participate in the net-zero transitions.

**Are there incentives for carbon capture, utilization, and storage? How?**

CCUS is not regarded as the main method of reducing emissions from the industry sector. Instead, the industry sector and CCUS were dealt with separately when the GHG emission reduction strategy of Korea was established. It was a prior premise to minimize the burden of CCUS by maximizing direct and process emission reduction levels of the industry. The Korean government is currently preparing support schemes to foster the CCUS service market in the near future.

**If relevant, what about recycling? What percentage is recycled? What are the obstacles to increase recycling? Is a policy to increase recycling already in place or in project?**

The Korean government recently announced ten tasks for achieving a Carbon-neutral society, which comprise the promotion of a circular economy. The "K-Circular Economy Innovation Roadmap" is going to be released before the end of 2021. It includes detailed plans for maximizing recycling and minimizing wastes, henceforth reducing GHG emissions from new product manufacturing. In addition, the 2050 Carbon-neutral Scenario for Korea includes the petrochemical industry going to pyrolyze 50% of all waste plastics in Korea and recycle them as plastic raw materials. Also, 60% of bituminous coal used by cement industry will be replaced by synthetic waste resins in 2050.

## Author Acknowledgements

---

*List of contributing experts to the CAETS 2022 Energy report*

**Chinho Park**, Executive Vice President, Korea Institute of Energy Technology

**Woong-seong Chang**, President, Institute of Innovation & Technology, Inha University

**Eun-mi Jung**, Executive Director/Research Fellow, Center for Growth Engine Industries,  
KIET (Korea Institute for Industrial Economics & Trade)

**Seung-eon Lee**, Senior Research Fellow, Department of Living & Built environment Research,  
Korea Institute of Civil Eng. & Building Technology

**Jae Ho Yun**, Principal Researcher, Korea institute of Energy Research

## Table of Contents

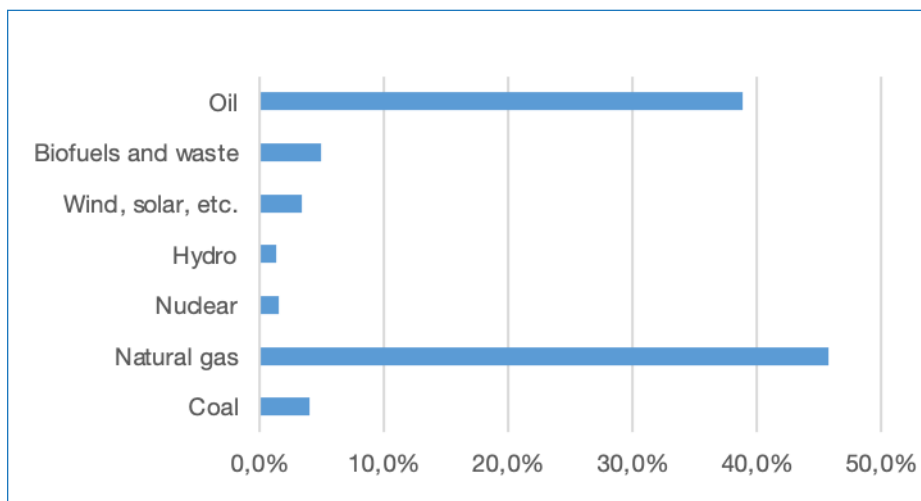
---

1.	National energy profile 2020 .....	359
2.	Energy perspectives 2030 - 2050 .....	363

## 1. National energy profile 2020

Mexico is a country with 126 014 024 inhabitants, energy production of 1 347 TWh and electricity production of 307.5 TWh. It had an average GHG emission of 381 Mt CO<sub>2</sub> equivalent in 2020. An overview of energy production by source of generation can be seen in the following graphs *Fig. 1.* and *Fig. 2.*

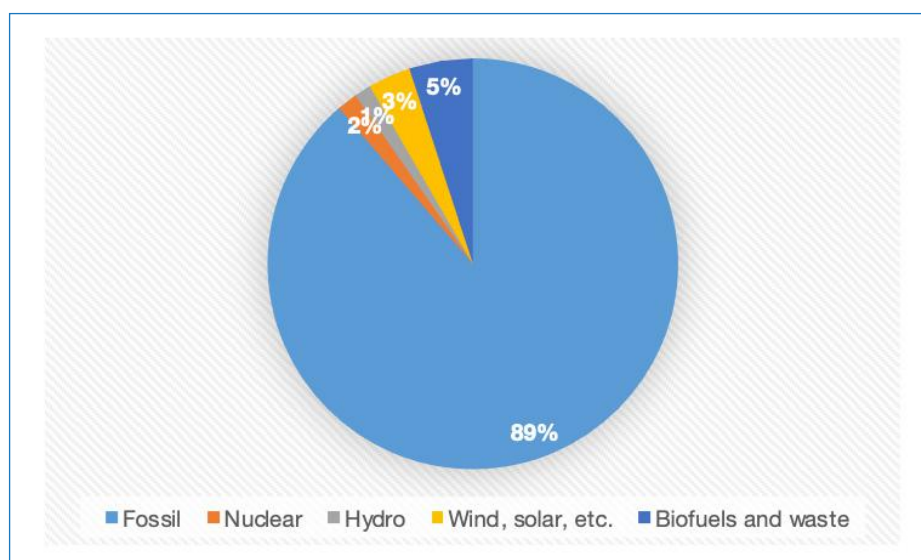
### Mexico energy supply



*Fig. 1.* Mexico energy supply by source 2020. Source: IEA, World Energy Balances:

<https://www.iea.org/data-and-statistics/data-product/world-energy-balances>

Documentation: [https://iea.blob.core.windows.net/assets/20a89a1b-634c-41f1-87d1-d218f07769fb/WORLDBAL\\_Documentation.pdf](https://iea.blob.core.windows.net/assets/20a89a1b-634c-41f1-87d1-d218f07769fb/WORLDBAL_Documentation.pdf)



*Fig. 2.* Fossil energy supply in Mexico 2020. International Energy Agency (IEA).

*Fig. 1.* and *Fig. 2.* show that energy supply in Mexico is fundamentally based on fossil fuels (87% to 89% – natural gas, oil and coal).

Fig. 3. below displays the evolution of the share of the various sources in the energy supply from 1990 to 2020.

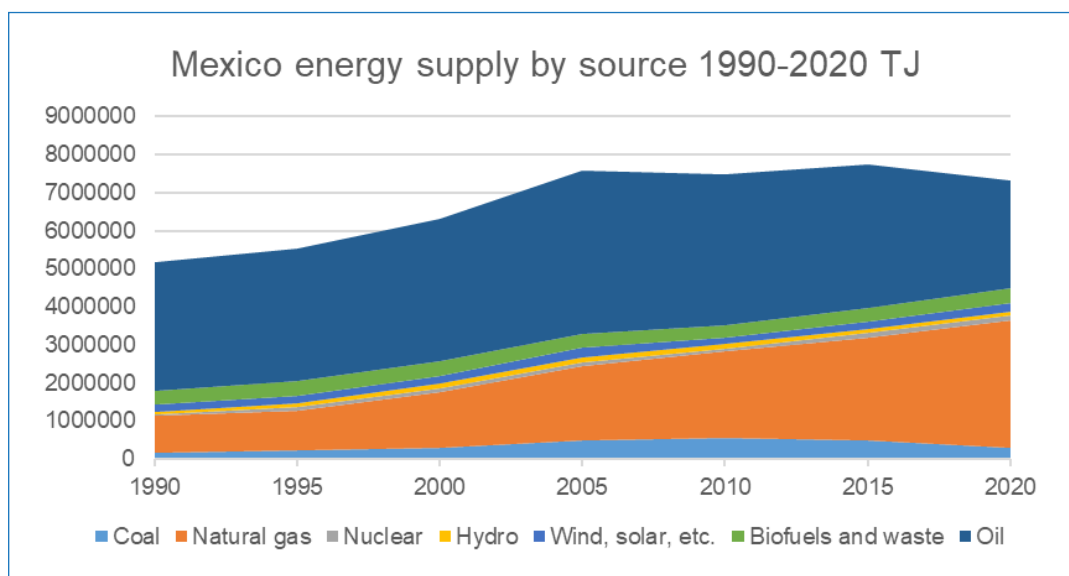


Fig. 3. Mexico energy supply by source 1990-2020, in TJ (1 MTJ = 278 TWh)  
Source: International Energy Agency (IEA).

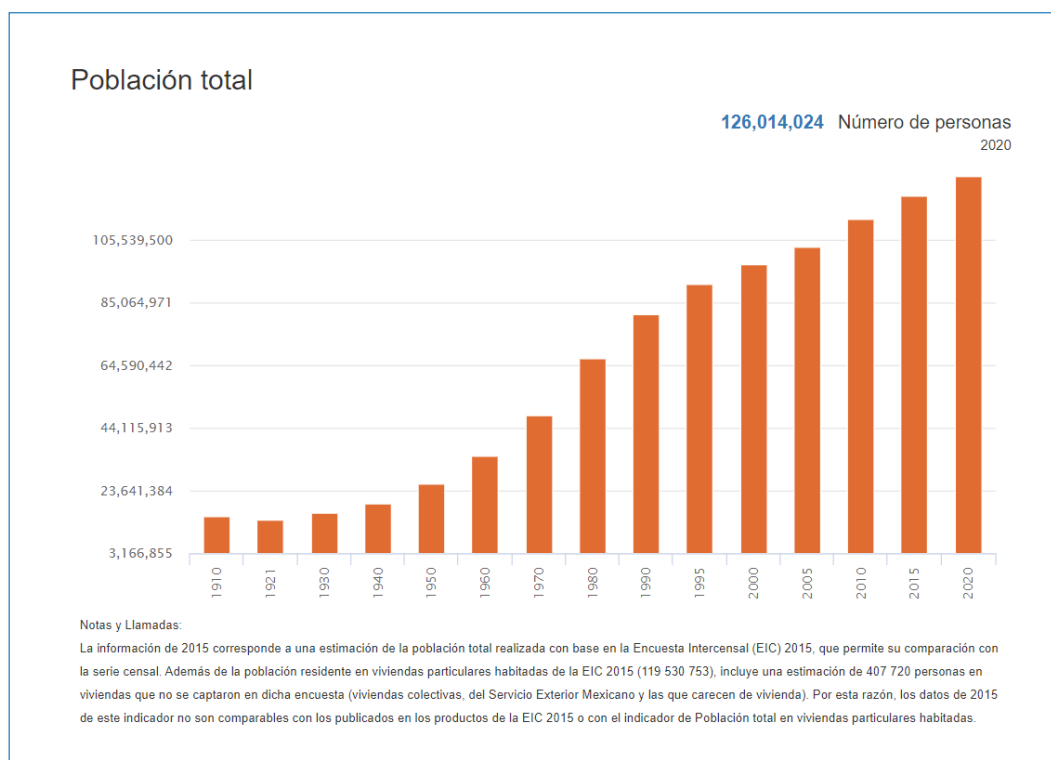
### Mexico yearly consumption

Table 1. below shows electricity consumption growing at a fast rate, more than tripling, between 1990 and 2020, while total energy consumption grew by only 39%. This is reflected in the ratio of electricity to total energy consumption increasing from 9.8% in 1990 to 22.8% in 2020.

Year	Energy Consumption (TWh)	Electricity Consumption (TWh)	Elec/Energy (%)
1990	969	95.5	9.8
1995	1 012	130.2	12.9
2000	1 108	178.1	16.1
2005	1 233	211.7	17.1
2010	1 364	230.3	16.9
2015	1 394	269.6	19.3
2019	1 346	305.0	22.7
2020	1 347	307.5	22.8

Table 1. Mexico yearly consumption: final energy, electricity (TWh) IEA

However, during that period of 30 years, population grew by 55.2%, from 81.2 million to 126 million. The next graph indeed presents data from INEGI, the Mexican Institute of Statistics and Geography (*Instituto Nacional de Estadística y Geografía*), on population growth from 1910 to 2020.



**Fig. 4.** Mexico Yearly population growth 1910 to 2020 by INEGI

Such increase in population leads us to consider per capita consumption, (energy and electricity consumption in the period 1990-2020).

Year	Inhabitants (millions) <sup>1</sup>	Energy consumption (TWh)	Energy consumption per person and per year (MWh/capita)	Electricity consumption (TWh)	Electricity consumption per person and per year (MWh/capita)
1990	81.2	969	11.9	95.5	1.17
1995	91.2	1 012	11.0	130.2	1.43
2000	97.5	1 108	11.4	178.1	1.83
2005	103.3	1 233	11.9	211.7	2.05
2010	112.3	1 364	12.1	230.3	2.05
2015	119.9	1 394	11.6	269.6	2.25
2019	125.3	1 346	10.7	305.0	2.40
2020	126.0	1 347	10.7	307.5	2.40

**Table 2.** Mexico yearly consumption per person: final energy, electricity (MWh per person per year) IEA.

As can be seen in *Table 2.*, per capita energy consumption remained fairly stable over the years from 1990 to 2010 with a slight decrease thereafter, whereas per capita electricity consumption about doubled up to 2020.

<sup>1</sup> Actualisation from INEGI (Instituto Nacional Estadística Geografía) and the International Energy Agency (IEA).  
<https://www.iea.org/data-and-statistics/data-tables?country=Mexico&energy=Balances&year=2019>  
and: <https://www.iea.org/data-and-statistics/data-browser/?country=Mexico&fuel=Energy%20consumption&indicator=TotElecCons>

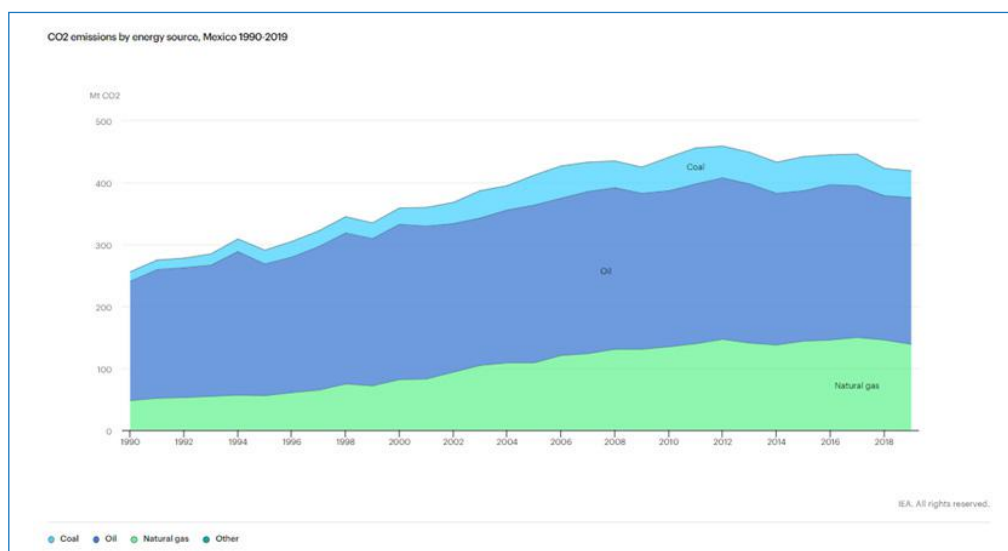
CO<sub>2</sub> emissions, fossil fuel emissions and energy carbon intensity

Year	Total CO <sub>2</sub> Emissions (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions from electricity (MtCO <sub>2</sub> )	CO <sub>2</sub> emissions per capita
1990	257.0	63.942	3.00
1995	291.3	83.127	3.10
2000	359.7	121.553	3.60
2005	412.4	134.662	3.90
2010	440.5	138.320	5.23
2015	442.4	142.927	4.50
2019	419.4	136.638	4.36
2020	381.0	124.920	3.05

**Table 3.** Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>).

Source: IEA

Fig 5. shows the various sources of CO<sub>2</sub> generation:



**Fig. 5.** Evolution of CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)

<https://www.iea.org/data-statistics/databrowser?country=MEXICO&fuel=CO2%20emissions&indicator=CO2BySource>

Fig. 5. draws attention to the following situations: 1) Emissions declined after 2012; 2) CO<sub>2</sub> emissions from liquid fuels have been at a higher level than those from gas.

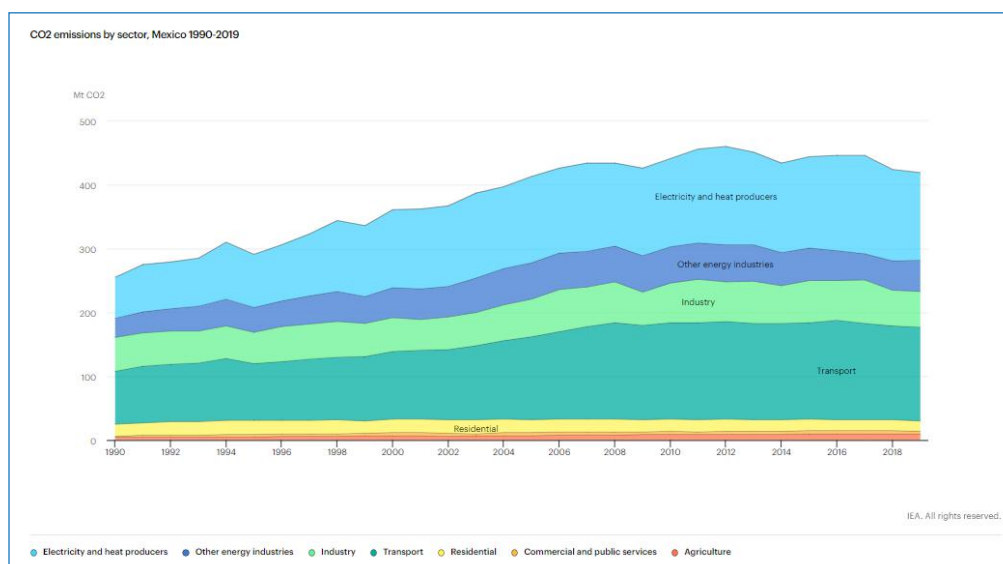


Fig. 6. Evolution of CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)

<https://www.iea.org/data-and-statistics/data-browser/?country=Mexico&fuel=CO2%20emissions&indicator=CO2BySector>

Fossil fuel emissions have risen for electricity and heat producers, as well as in transport. Emissions from industry and other sources have remained stable. This graph is consistent with high fossil fuel-consuming countries.

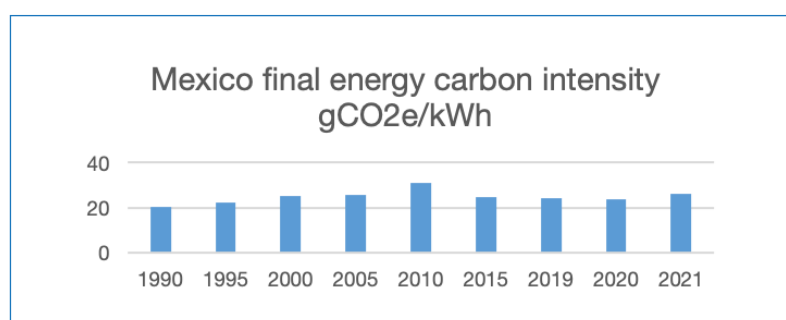


Fig. 7. Mexico final energy carbon intensity: gCO<sub>2e</sub>/kWh. produced with IEA Data.

## 2. Energy perspectives 2030 - 2050

**Does your country have national roadmaps regarding energy production and GHG emissions? What legal status do these documents have? What is their timeline?**

There is no quantified plan that could be regarded as a real action guide, the reason being that the current government intends to change the Hydrocarbons and Electricity Law passed in 2013-2014, which was designed on the basis of free competition in the electricity market, including the state-owned company *Comisión Federal de Electricidad* (CFE). A reform of the electricity industry aims at the centralisation of electricity generation up to 54% for CFE, regardless of kWh prices, and leaves the remaining 46% to small private industrial companies as long as their production capacity does not exceed one MW and do not involve self-supplying partners.

This situation has aroused controversy and is currently being debated in the Chamber of Deputies. As long as there is no defined plan, there will not be enough elements for describing perspectives. Currently, the Energy Secretary of Mexico (SENER)<sup>2</sup> estimates that by 2024, CFE and private actors will incorporate a total of 1 219 MW new power plants, 50% of which being combined cycle and 50% PV and wind. However, neither a

<sup>2</sup> Academia de Ingeniería México

schedule nor further details of capacities and locations are presented. In order to define the Law, every five years since 2020, the Academy of Engineering carried out the following exercise based on population growth 2025-2050.

On 30 June 2021, SENER unveiled the new Program for the Development of the National Electricity System 2021-2035. Von Wobeser y Sierra S.C.

#### Forecast electric generation in Mexico

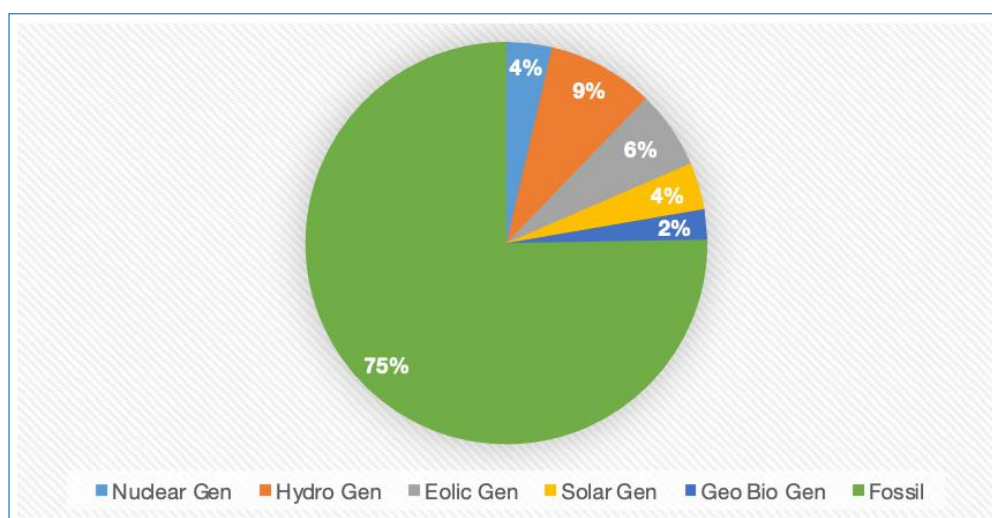
#	Concept (TWh)	2025	2030	2035	2040	2045	2050	Comments
1	Electricity gen**	331.3	348.0	365.3	383.4	402.4	422.3	Beta x <= 80%
2	Nuclear gen	17.1	22.8	28.5	34.2	39.9	45.6	6 new nuclear plants***
3	Hydro gen	27.9	30.7	33.8	37.2	40.9	45.0	Gov. investment
4	Eolic gen	25.0	35.0	45.0	55.0	60.0	65.0	Linear private CFE
5	PV gen	17.8	23.7	29.7	35.6	53.4	60.0	Linear private CFE
6	Geo bio gen	11.4	17.1	25.6	38.5	38.5	38.5	Linear private CFE
7	Renewable (4+5+6)	54.2	75.8	100.3	129.1	151.9	163.5	
8	Non Fossil (2+3+7)	99.3	129.4	162.6	200.5	232.7	254.1	
9	Fossil (1-8)	232.0	218.6	202.7	182.9	169.6	168.2	39.84%

**Table 4.** Mexico Forecast\* Electric generation by source 2020-2050 in TWh

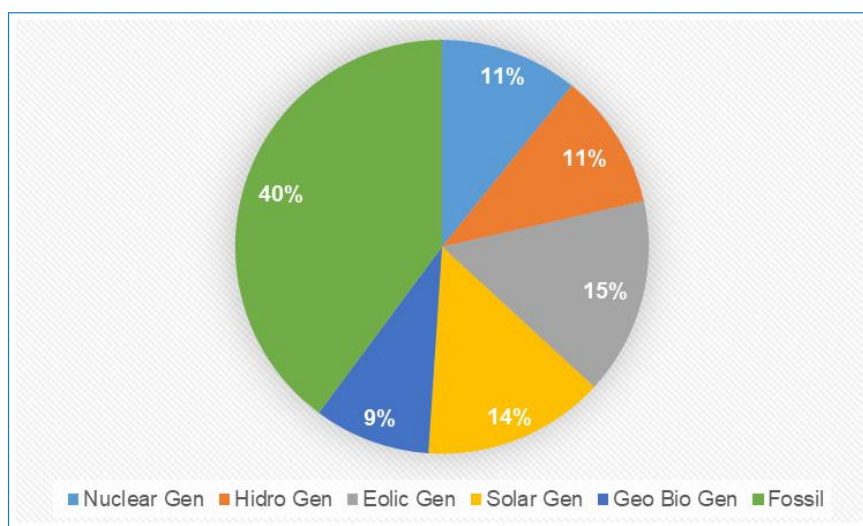
\* Academia de Ingeniería México, \*\*base data British Petroleum BP, \*\*\*Invest by cycle

This forecast was made on the basis of a stochastic modelling  $\beta$  (Beta  $x \leq 80\%$ ), from population growth projections. The projections for each production source were based on the observed behaviour shown in the comments of the table, with a mixed private-CFE investment. In the case of nuclear production, it was assumed that full life-cycle external financing will exist.

The results are clearer if we look at the following two charts, which show that the use of fossil fuels for electricity generation will decrease from 75% (2020) to 40% (2050) but will not reach 0%. This is because of the need for large investments, although the use of all other non-fossil sources does increase to satisfy expanding electrical energy requirements due to population growth, etc.



**Fig. 8.** Mexico electric generation by source 2020. BP.



**Fig. 9.** Mexico forecast\* electric generation by source 2050. AIM and BP.

\* Academia de Ingeniería México

The Graph for the year 2050 shows two very important sources may compensate for the intermittency that occurs with renewable sources, such as wind and solar (eolic and PV). These sources are nuclear (11%) and hydro (11%) power, as their production can be constant. In these cases, it is very important to contemplate full-cycle financing as GHG emissions must be as much reduced as possible, in a central way, while the water problem in Mexico is also an urgent issue.

#### **Roadmap for the energy mix**

Mexico signed the Paris and Glasgow Agreements, and committed to significantly reducing GHG and using clean energy. However, Petróleos Mexicanos (Pemex) is building a new 340 million barrels per day (Mbd) Gulf Coast refinery, purchased the remaining 50% of the Dear Park refinery in Texas USA and will complete a coker plant in central Mexico.

It is believed that even under these new foreseeable emissions, solutions must be proposed to reduce GHGs. The following possibilities are expressed below:

- 1) suspend the operation of three of the oldest of the six existing refineries;
- 2) provide intensive maintenance to the remaining refineries and upgrade the control systems;
- 3) complete the coker plant;
- 4) invest in gasification plants with the intention of producing a) Methanol, b) Ammonia for petrochemicals and fertilisers;
- 5) reduce the use of fuel oil in electricity production as much as possible;
- 6) encourage the use of hydropower;
- 7) encourage the use of nuclear power;
- 8) campaign for the use of wind and solar energy (PV).

According to our estimate, if this or other comparable solutions are not implemented, Mexico will not reach 40% of fossil fuel utilisation by 2050.

### Roadmap for the reduction of GHG emissions (country, per capita)

The General Law on Climate Change defines the National Inventory of Greenhouse Gas and Compound Emissions (INGELYCEI) as the document containing the estimate of anthropogenic emissions by sources and removals by sinks in Mexico. The following graph shows the per capita consumption in MWh and GHG emissions in MtCO<sub>2e</sub>.

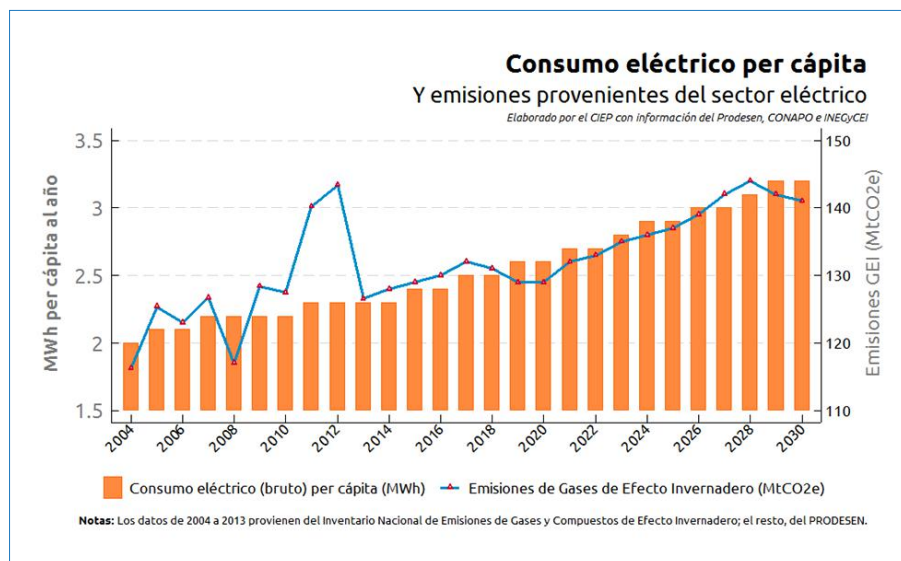
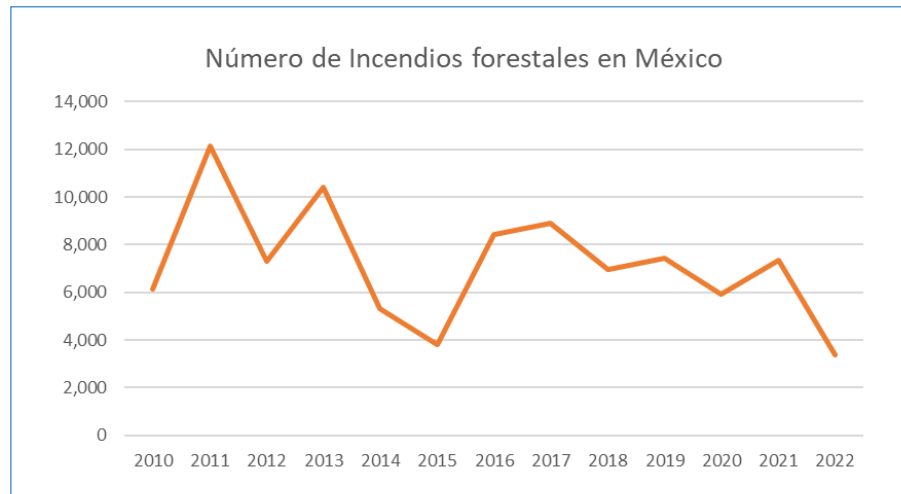


Fig. 10. Per capita yearly electric consumption in MWh and GHG emissions in MtCO<sub>2e</sub> (data in Spanish)

In Fig. 10., the year 2021 has not been updated with the following data: 136 MtCO<sub>2e</sub> and 26.16 gCO<sub>2</sub>/kWh. Two situations merit special attention: one in 2012 and the other regarding the growth of CO<sub>2</sub> emissions from 2013 until 2028. Explanation is provided in the Fig. 11. below.



SEMARNAT Comisión Nacional Forestal, Gerencia del Manejo del Fuego, Abril, 2022.

Fig. 11. Number of excess forest fires presented 2010-2013

As can be seen, in the period from 2010 to 2013 there were a large number of forest fires whose emissions were recorded in the atmosphere as CO<sub>2</sub>.

In order to understand the answers to this questionnaire, it is important to take into account that the different, partly toxic compounds that form GHGs in Mexico reach a very high concentration level in the Mexico Basin (Mexico City).

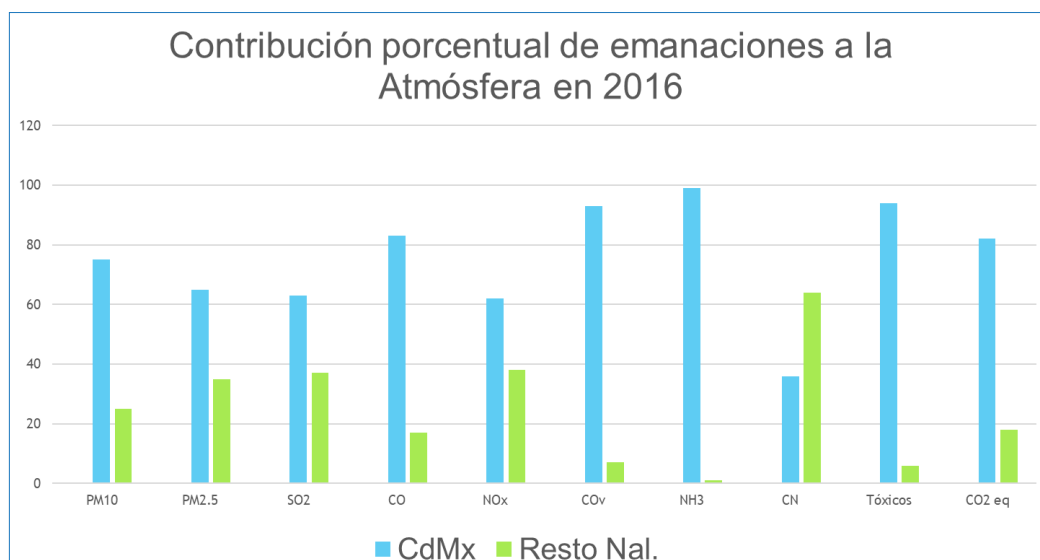


Fig. 12. Percent contribution of emissions of Mexico City (Ciudad de México, CdMx), and rest of Mexico SECC (In Spanish)

Fig. 12. shows that this is a phenomenon in which the concentration of emitted gases becomes highly hazardous to health. To control the toxic concentrations around the population, an hourly monitoring procedure has been implemented in several laboratories in Mexico City (and in other places too) and an indicator has been established, the Metropolitan Air Quality Index (IMECA).

As an example, in Fig. 13., IMECA values for PM<sub>10</sub> (particle size <10 microns) and Ozone are presented. Other examples are shown in Table 5., where the tolerated upper limits for some contaminants, microbiological and COVID-19 are listed.

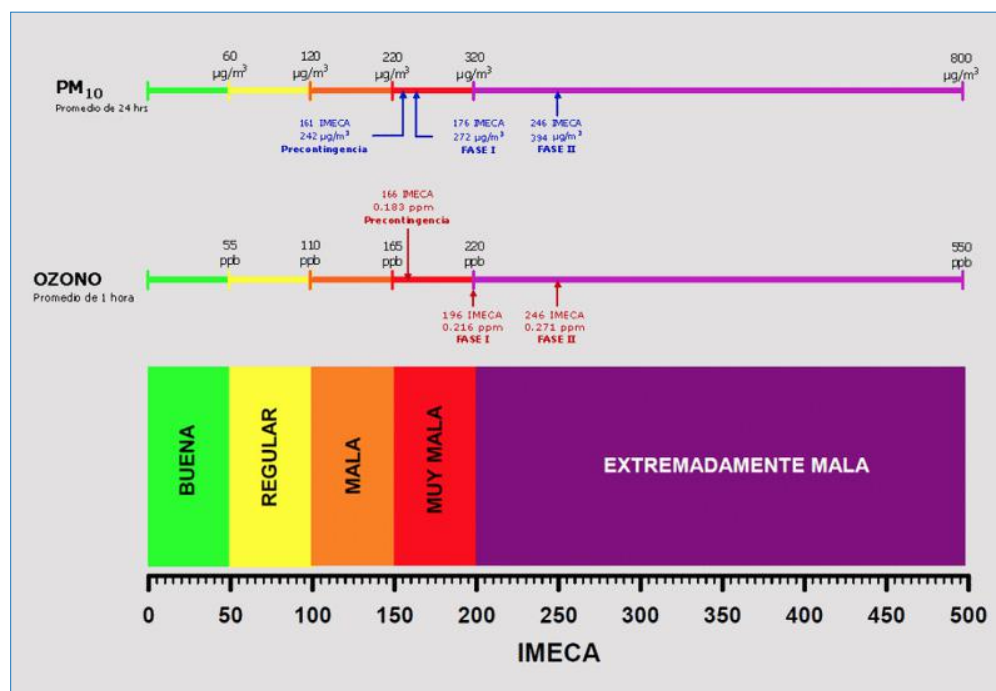


Fig. 13. IMECA value for PM<sub>10</sub> and Ozone (In Spanish)

Mediciones IAQ con instrumentos calibrados de medida		Estado	Valor límite
Dióxido de Carbono	CO2	●	Lim. 2500ppm
Monóxido de Carbono	CO	●	< 5ppm
Humedad Relativa	HR	●	30%-70%
Temperatura interior	T <sup>a</sup>	●	21°-23° (+/- 1°C)
Material particulado PM2,5	PM2,5	●	<20µg/m3
Material particulado PM10	PM10	●	<40µg/m3
Conteo partículas PM0,5	PM0,5	●	<35.200.000p/m3
Conteo partículas PM5	PM5	●	<293.000p/m3
Inspección del sistema de climatización y ventilación (HVAC)		Estado	Valor límite
Inspección visual sistema HVAC		●	Limpio
Inspección microbiológica - Control ambiental		●	<800 ufc/100m3
Inspección microbiológica - Control de superficie		●	<100 ufc/25cm2
Inspección de materia particulada Impulsión/Retorno		●	<10 µg/100cm2
Inspección de materia particulada Extracción		●	<60 µg/100cm2
Monitorización continua		Estado	Valor límite
Dióxido de Carbono	CO2	●	Lim. 2500ppm
Humedad Relativa	HR	●	30%-70%
Temperatura interior	T <sup>a</sup>	●	21°-23° (+/- 1°C)
Compuestos Orgánicos Volátiles	COV	●	<220ppb
Formaldehído		●	<120µg/m3
Mediciones microbiológicas y detección de COVID-19		Estado	Valor límite
Recuento de aeróbios a 22°C en superficie		●	<4 UFC/cm2
Recuento de aeróbios a 22°C en aire		●	<600 UFC/m3
Recuento de hongos en superficie		●	<1 UFC/cm2
Recuento de hongos en aire respirable		●	<200 UFC/m3
Detección SARS-CoV-2		●	Detectable

Table 5. Tolerated upper limits for some contaminants, microbiological and COVID-19 (In Spanish)

## CO<sub>2</sub> emissions from electricity production

See Fig. 10. page 366 above, Per capita yearly electric consumption in MWh and GHG emissions (MtCO<sub>2e</sub>).

## Electricity to end-uses 2020

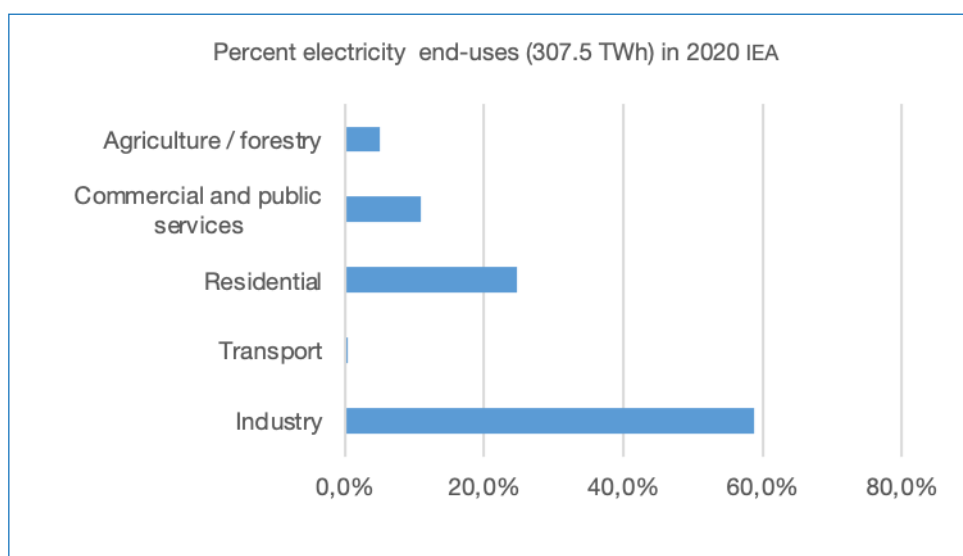


Fig. 14. Percent electricity end uses (307.5 TWh) in 2020

## Table of Contents

---

1.	National energy profile 2019 .....	370
2.	Energy perspectives 2030 - 2050 .....	374
3.	Industry, Buildings, and Agriculture .....	379
3.1.	Food & Agriculture .....	379

## 1. National energy profile 2019

The national energy profile discussed herein is based primarily on data obtained from the IEA website. In a few cases where the relevant information is unavailable, the required data is sourced from other reliable agencies with independent strong data correlation to the IEA database. In such cases, appropriate referencing is provided.

### Total yearly consumption: final energy, electricity (TWh)

Year	Energy Consumption (TWh)	Electricity Consumption (TWh)	Elec/Energy (%)
1990	692	10.8	1.6
1995	784	12.7	1.6
2000	911	11.8	1.3
2005	1 088	18.8	1.7
2010	1 237	22.2	1.8
2015	1 465	27.6	1.9
2019	1 576	26.7	1.7

**Table 1.** Comparison between total energy and electricity consumption between 1990-2019

**Source:** IEA World Energy Balances <https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances>  
<https://www.iea.org/countries/nigeria>

It is obvious that despite the increase in final energy consumption (130%) and electricity usage (145%) over the period shown, there has only been a marginal improvement (12.5%) in the ratio of electricity-to-total energy consumption in the country probably because of the relatively low grid infrastructure development over that period.

### Per capita yearly final energy and electricity consumptions (MWh)

Year	Inhabitants (per million)	Energy Consumption (TWh)	Energy Consumption per person and per year (MWh)	Electricity Consumption (TWh)	Electricity Consumption per person and per year (MWh)
1990	95.2	690	7.2	10.8	0.1
1995	107.9	784	7.3	12.7	0.1
2000	122.3	911	7.5	11.8	0.1
2005	138.9	1 088	7.8	18.8	0.1
2010	158.5	1 237	7.8	22.2	0.1
2015	181.1	1 465	8.1	27.6	0.2
2019	201.0	1 576	7.8	26.7	0.1

**Table 2.** Per capita total energy and electricity consumption over the past three decades

**Source:** IEA World Energy Balances <https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances>  
**Source:** IEA Data Services <https://www.iea.org/data-and-statistics/data-products>

The relatively low per capita electricity consumption trend (from 0.113 to 0.152 MWh/person) between 1990 to 2019 seen in Table 2 is consistent with the previous inference from data in Table 1. By comparison, both South Africa and Egypt reflect an average per capita electricity consumption of 4.3 and 1.2 MWh/person respectively over the same period.

**Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>),  
total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)**

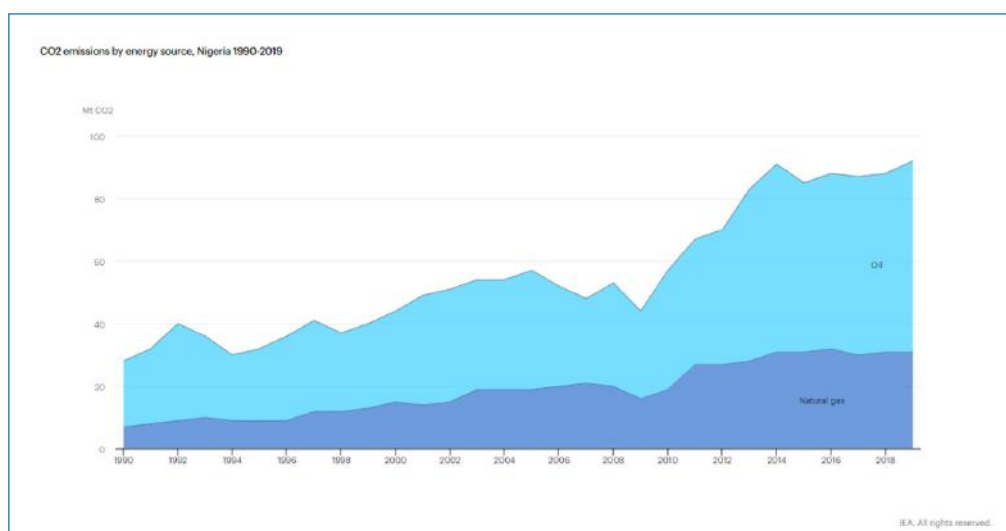
Year	Total CO <sub>2</sub> Emissions (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions from electricity (MtCO <sub>2</sub> )	CO <sub>2</sub> emissions per capita
1990	28.1	5.7	0.3
1995	32.8	5.4	0.3
2000	43.7	6.7	0.4
2005	56.6	8.0	0.4
2010	56.9	7.9	0.4
2015	84.8	13.5	0.5
2019	92.0	12.9	0.5

**Table 3.** CO<sub>2</sub> emissions metrics for the 1990-2019 period

**Source:** IEA Greenhouse Gas Emissions from Energy <https://www.iea.org/data-and-statistics/data-product/co2-emissions-from-fuel-combustion>

CO<sub>2</sub> emissions, mainly from anthropogenic activities, include release from the energy industries such as oil and gas, transport, heat and electricity producers, residential buildings and other industries (e.g chemicals and cement manufacturing). *Table 3* shows that CO<sub>2</sub> released from electricity accounts for 14-20% during this period. The emissions history is an S-shaped behaviour which suggests that the growth in CO<sub>2</sub> emissions from fossil fuels utilization in the first two decades has nearly plateaued in recent years but not declined indicating weak government efforts on carbon reduction since other economies have revealed a steady downward trend in annual CO<sub>2</sub> emissions within the past decade.

**CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)**



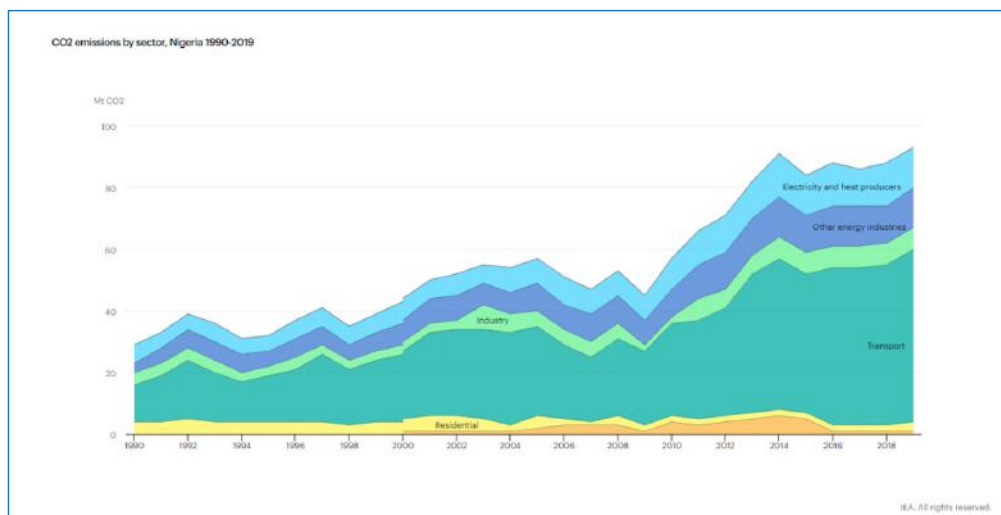
**Fig. 1.** CO<sub>2</sub> emissions trend by source from 1990 to 2019.

Data from IEA, Data & Statistics

<https://www.iea.org/data-and-statistics/data-browser?country=NIGERIA&fuel=CO2%20emissions&indicator=CO2BySource>

This plot implicates Nigeria's strong reliance on fossil fuel combustion for energy provision since the trend essentially parallels the growth in energy consumption. The higher amounts of CO<sub>2</sub> released through oil utilization compared to natural gas seems consistent with the fact that Nigeria is the largest user of oil-fired generators (backup for electricity) on the continent while most (80%) of its power production is derived from natural gas.

## CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)



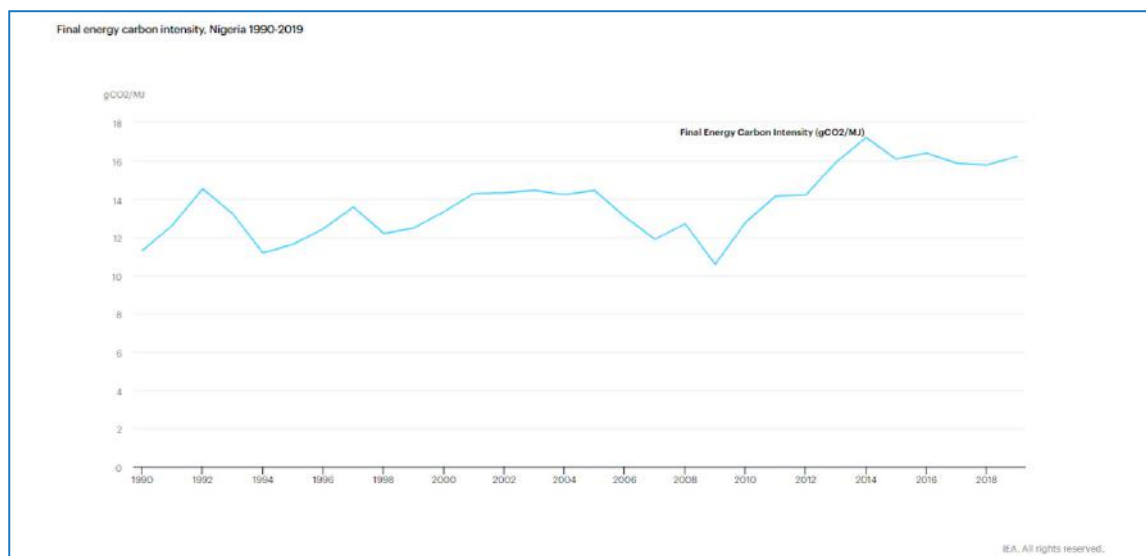
**Fig. 2.** CO<sub>2</sub> emissions profile according to the producing sector over the period, 1990-2019

Data from IEA, Data & Statistics

<https://www.iea.org/data-and-statistics/data-browser?country=NIGERIA&fuel=CO2%20emissions&indicator=CO2BySector>

From this figure, the most significant polluter is the transport sector, contributing between 40-60% of the annual CO<sub>2</sub> emissions. This suggests that the incentive for nationwide electric vehicle adoption as a means of attaining the global zero GHG emissions target should be part of the decarbonization strategy, especially since Nigeria has the second largest automotive market on the continent.

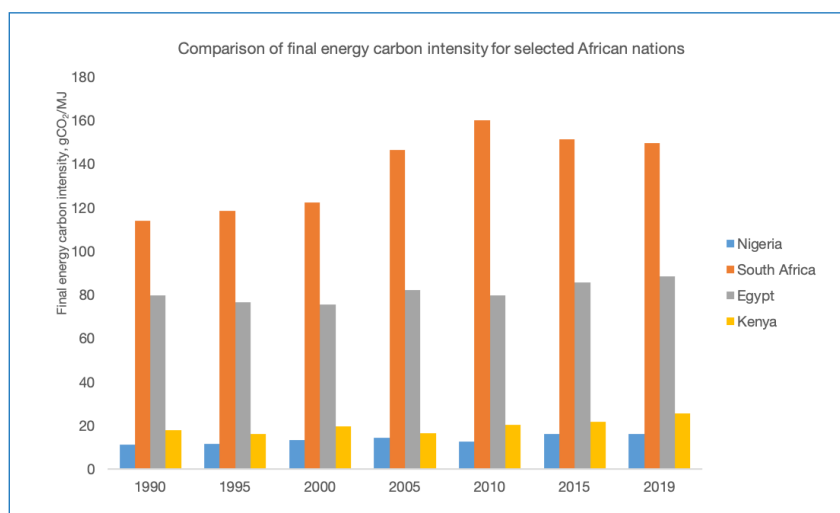
## Final energy carbon intensity: gCO<sub>2</sub>/MJ and gCO<sub>2</sub>/kWh (1 Megajoule = 0.27778 Kilowatt hours)



**Fig. 3.** History of the final energy carbon intensity between 1990 to 2019

<https://www.iea.org/data-and-statistics/data-browser?country=NIGERIA&fuel=CO2%20emissions&indicator=FECI>

This energy metric is an indicator of the impact of GHG release per unit energy consumed in the economy. The comparison with other big economies on the continent is shown in Fig. 4. The comparatively lower value for Nigeria is probably due to the low dependency on coal as a principal contributor to the national energy consumption compared to South Africa.



**Fig. 4.** Comparison of final energy carbon intensity between some African countries

### Electricity Carbon intensity: gCO<sub>2</sub>/kWh

Year	Electricity consumption (TWh)	CO <sub>2</sub> Emissions from electricity (MtCO <sub>2</sub> )	Electricity carbon intensity (gCO <sub>2</sub> /kWh)
1990	10.8	5.7	528.3
1995	12.7	5.4	424.0
2000	11.9	6.7	569.7
2005	18.8	8.0	422.7
2010	22.2	10.0	449.1
2015	27.6	13.5	488.8
2019	26.7	12.9	481.8

**Table 4.** Electricity consumption & carbon metrics for the period, 1990 to 2019

**Source:** IEA Energy and Carbon Tracker 2020 <https://www.iea.org/data-and-statistics/data-product/iea-energy-and-carbon-tracker-2020>

The electricity carbon intensity measures the impact of CO<sub>2</sub> release from electricity consumption alone. These values are about an order of magnitude higher than the final energy carbon intensity when compared with data from *Fig. 3* (using a conversion factor of 1 MJ= 0.2778 kWh). This suggests that the impact of CO<sub>2</sub> due to electricity consumption is about 10 times higher than that for final (overall) energy consumption in Nigeria even though it is not the biggest contributor to CO<sub>2</sub> emissions. However, as may be seen in *Fig. 5*, both South Africa and Egypt (the continent's second and third largest economies respectively) surpassed Nigeria. Clearly, there is a need for more serious adoption of low-carbon electricity technologies in Nigeria.

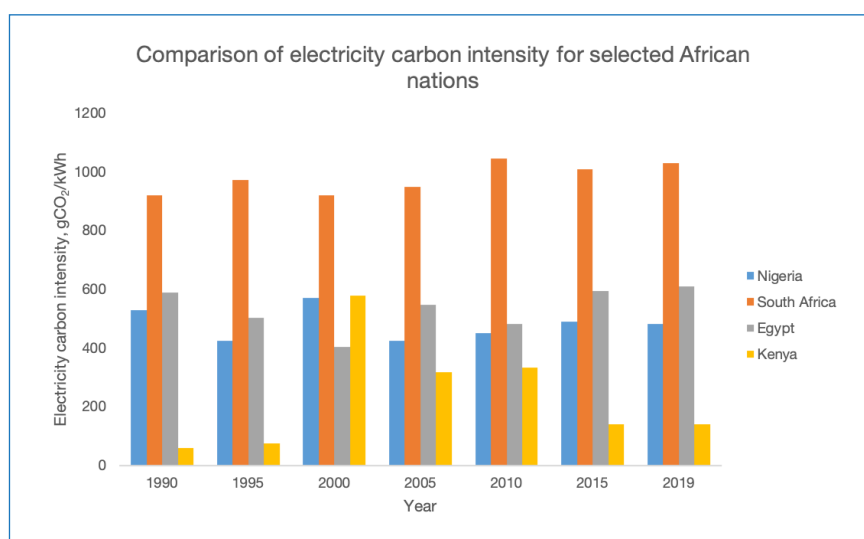


Fig. 5. Time trajectory of electricity carbon intensity for some African countries

## 2. Energy perspectives 2030 - 2050

### Does your country have national roadmaps regarding energy production and GHG emissions? What legal status do these documents have? What is their timeline?

Nigeria relies on natural gas to meet a large proportion (ca. 80%) of its energy needs. In 2020, the country adopted a National Economic Sustainable Plan<sup>1</sup> which includes the National Gas Expansion Program (NGEP) which will accelerate the development of petroleum liquified gas for domestic consumption and compressed natural gas for the global export market. Based on the 2019 Presidential Power Initiative, the country has instituted an electrification roadmap (in partnership with Siemens AG) that consists of three phases to achieve 80% electricity access by 2025. This 6-year program is on track so far (Phase 1 – 2021) to deliver the expected outcomes (25 GW).

At present, the country's per capita GHG emissions are estimated at 3.37 t CO<sub>2</sub>,equiv. However, Nigeria has a 2050 zero emissions target and a nationally determined contribution (NDC) of 442.5 M t CO<sub>2</sub>,equiv by 2030 which translates to a per capita GHG release of about 1.7 t CO<sub>2</sub>,equiv. Nigeria is also a signatory to the Global Methane Pledge and has committed to reducing emissions by 2030. The country's current GHG efforts have produced a 5-year (2012-2017) drop of about 6.4% in per capita emissions according to the 2020 Climate Transparency Report.

The Federal government also launched a National Renewable Energy Master Plan in 2015. Among others, the aim is to improve the diversification of the national energy mix through increased renewable energy resource (hydro, solar-PV, solar-thermal, wind, biomass, etc). Although hydro-generation has been the main renewable electricity source in Nigeria since 2015 the input from solar has grown from about 7% to 14% (2019) of the total electricity supply. It is anticipated that an installed capacity for combined renewable electricity production should reach 2940 MW (small hydro – 2000 MW, solar- 500 MW, biomass – 400 MW, wind – 40 MW) by 2025 to account for, at least, 10% of the total electricity. To accelerate the implementation of the renewable energy plan, the government has instituted a dedicated body, Nigerian Renewable Energy Agency (NREA) to look after its affairs in this respect. It has also provided custom duty exemption for imported renewable energy technologies, tax credits, capital incentives and preferential loan opportunities as catalysts for the development of the renewable energy sector.

<sup>1</sup> <https://budgetoffice.gov.ng/index.php/nigeria-economic-sustainability-plan>

## References

<https://www.climate-transparency.org/wp-content/uploads/2021/01/Nigeria-CT-2020.pdf>

[https://www.all-on.com/media/publications/simplified-guides-to-nigerias-energy-access-policies-and-regulations/\\_jcr\\_content/par/textimage.stream/1595008849973/dc8fea0b5aef03ead699def51ac37ec5be56b8e1/national-policy-on-climate-change-npcc.pdf](https://www.all-on.com/media/publications/simplified-guides-to-nigerias-energy-access-policies-and-regulations/_jcr_content/par/textimage.stream/1595008849973/dc8fea0b5aef03ead699def51ac37ec5be56b8e1/national-policy-on-climate-change-npcc.pdf)

<https://climatechangenews.com/2022/03/11/will-nigerias-climate-change-law-put-the-brakes-on-gas-flaring/#:~:text=The%20country%20also%20signed%20into,net%20zero%20emissions%20by%202060.>

[www.climate-transparency.org](https://www.climate-transparency.org)

<https://www.iea.org/policies/4967-renewable-energy-master-plan>

## Roadmap for the energy mix

Nigeria's roadmap for energy mix is based on the African Union's Agenda 2063 announced in 2015. This is a strategic framework for guiding the continent in its realisation of inclusive and sustainable development for its people by 2063. The National Energy Policy for Nigeria has among its objectives,

- To ensure the development of the nation's energy resources, with diversified energy resource options, for the achievement of national energy security and an efficient energy delivery system with optimal resources mix.
- To guarantee an adequate, reliable and sustainable supply of energy at appropriate costs and in an environmentally friendly manner, to the various sectors of the economy for national development
- To successfully use the nation's abundant energy resources to promote international cooperation.

As a result, the country has embarked on a multilateral energy transition timetable that allows for continuing investment in African gas energy resources (as a transition fuel) while recognizing the global shift towards a renewable energy platform. Specifically, Nigeria's planned energy demand mix based on the continent's Agenda 2063 is:

Year	Coal (TWh)	Oil (TWh)	Natural Gas (TWh)	Hydro (TWh)	Solar-PV (TWh)	Other Low-carbon tech. (TWh)	Bioenergy (TWh)	GDP (2018 US\$ bn)
2010		244	93			N.A.	1 140	919
2018		302	174			N.A.	1 326	1 169
2030	70	500	233	12	12	N.A.	442	2 058
2040	105	616	407	35	23	N.A.	512	3 678

**Table 5.** Projection for the Nigeria energy demand (2010-2040) for the Africa Case\*

Data from: <https://www.iea.org/articles/nigeria-energy-outlook>

\*Africa Case (Agenda 2063) assumes rapid economic and industrial development with complete realization of key UN Sustainable Development Goals including 100% electricity accessibility clean cooking by the populace as well as substantial reduction of infant mortality due to pollution.

It is obvious from *Table 5* that Nigeria (and African nations in general) still intends to include significant carbon-based energy in its short- and medium-term strategy for energy supply while transitioning to a completely renewable energy mix before the end of the 21<sup>st</sup> century.

## References

<https://www.energyforgrowth.org/memo/nigerias-electrification-roadmap-after-two-years-where-does-it-stand/>

<https://www.dlapiper.com/en/uk/insights/publications/2021/11/igeri-energy-futures/igeri-energy-futures-nigeria/>

<https://www.iea.org/articles/igeri-energy-outlook>

## Roadmap for the GHG emissions (country, per capita)

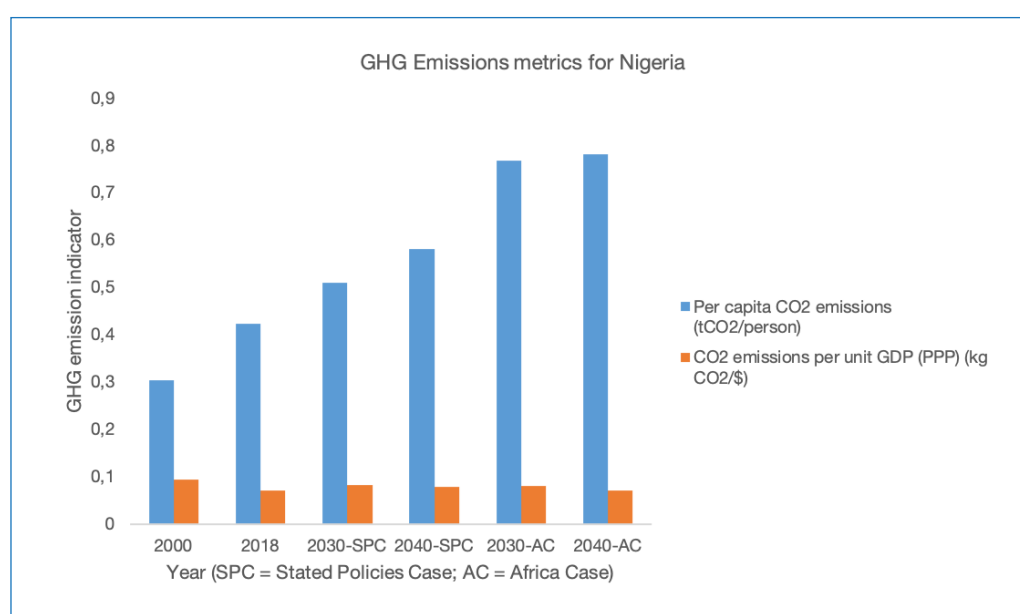
The country's roadmap for GHG emissions is intricately tied to its national energy policy as implicated in the preceding section. While the strong dependence on natural gas as an energy resource will be evident in the short- and medium-term strategies for the country, the present policy that has produced a continuing decrease (-6.4%) in GHG emissions suggests that planned improvement in renewable energy content of the supply mix would lead to further drop in GHG emissions till about 2040. This is deducible from the IEA data displayed below.

			State Policies Case**		Africa Case	
	2000	2018	2030	2040	2030	2040
Population (million)	122	196	263	329	236	329
% with electricity access	40	60	80	85	100	100
% with access to clean cooking	1	10	28	38	100	100
CO <sub>2</sub> emissions (Mt CO <sub>2</sub> )	37	83	134	191	181	257
GDP (2018 US\$ bn, PPP)	392	1 169	1 636	2 420	2 258	3 678

**Table 6.** Nigeria key indicators and policy initiatives

\*\*Stated Policies Case: is representative of IEA's assessment of the country's current policy frameworks and plans, taking into account the regulatory, institutional, infrastructure and financial circumstances that shape the prospects for their implementation.

It is apparent that if the current Nigerian government policies (Stated Policies Case) are maintained into the next two decades (up to 2040), GHG emissions will be further cut back than if the continent's Agenda 2063 (Africa Case) strategy was adopted. This may be due to the fact that the entire population is expected to have access to clean cooking than under the SPC where the accessibility to clean cooking is relatively lower (28% and 38% for 2030 and 2040 respectively). However, the country's expected GDP values are higher under the AC scenario than for the SPC. In view of the population growth over the next two decades, the per capita CO<sub>2</sub> emission and carbon cost to the economy have also been evaluated as shown in *Fig. 6*. This bar chart indicates that the average Nigerian may have reduced carbon footprint on the environment under the SPC regime than the AC although the carbon cost (2018 US\$ basis) will be stable (0.078 kg CO<sub>2</sub>/)\$ over the two-decade period.



**Fig. 6.** Trajectory of GHG emissions metrics between 2000-2040 for SPC and AC scenarios

## References

<https://www.offshore-energy.biz/nigeria-vows-to-reach-net-zero-by-2060-highlights-key-role-of-gas-in-energy-transition/#:~:text=Home%20Fossil%20Energy,Nigeria%20vows%20to%20reach%20net%20zero%20by%202060%2C%20highlights%20key,of%20gas%20in%20energy%20transition&text=During%20the%20COP26%20summit%20in,the%20country's%20energy%20transition%20roadmap.>

[https://unfccc.int/sites/default/files/resource/Nigeria\\_LTS1.pdf](https://unfccc.int/sites/default/files/resource/Nigeria_LTS1.pdf)

<https://climateactiontracker.org/climate-target-update-tracker/nigeria/>

<https://www.premiumtimesng.com/news/headlines/493083-analysis-cop26-nigerias-plan-to-cut-carbon-emission-to-net-zero-by-2060-is-short-on-details.html>

## Roadmap for the electricity mix

Fig. 7 shows the IEA data for the projected electricity generation mix for Nigeria using the country's Stated Policies and Agenda 2063 scenarios.

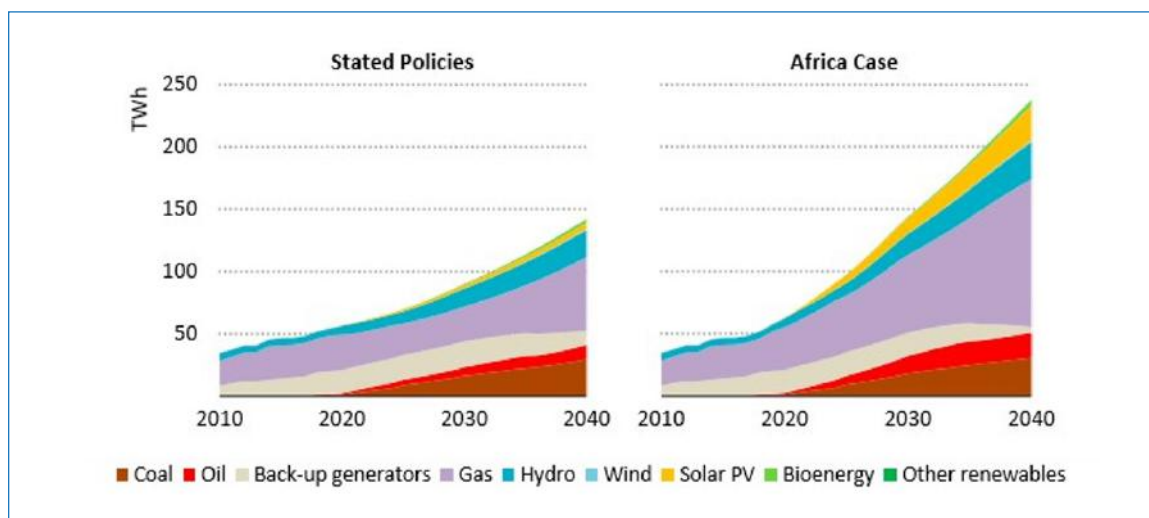


Fig. 7. Electricity generation projection from different technologies under SPC and AC scenarios

As expected, electricity generation ramped up significantly between 2020 to 2040 in the AC scenario more than in the SPC since the former assumes total electricity accessibility by 2030 compared to the latter which hopes for 80% accessibility in the same year. Although electricity from back-up generators peaks (at ca. 20 TWh) around 2030 under both scenarios, by 2040 this would have dropped to just 5 TWh for AC while SPC would still allow production at 11 TWh. Even so, under the two cases, reliance on fossil fuels continues to grow until 2040 while the percentage contribution to electricity mix decreased (from 82% to 78% for SPC and 82% to 72% for AC between 2010 to 2040). Accordingly, Fig. 8 reveals that renewable electricity contribution is better under the AC than the SPC.

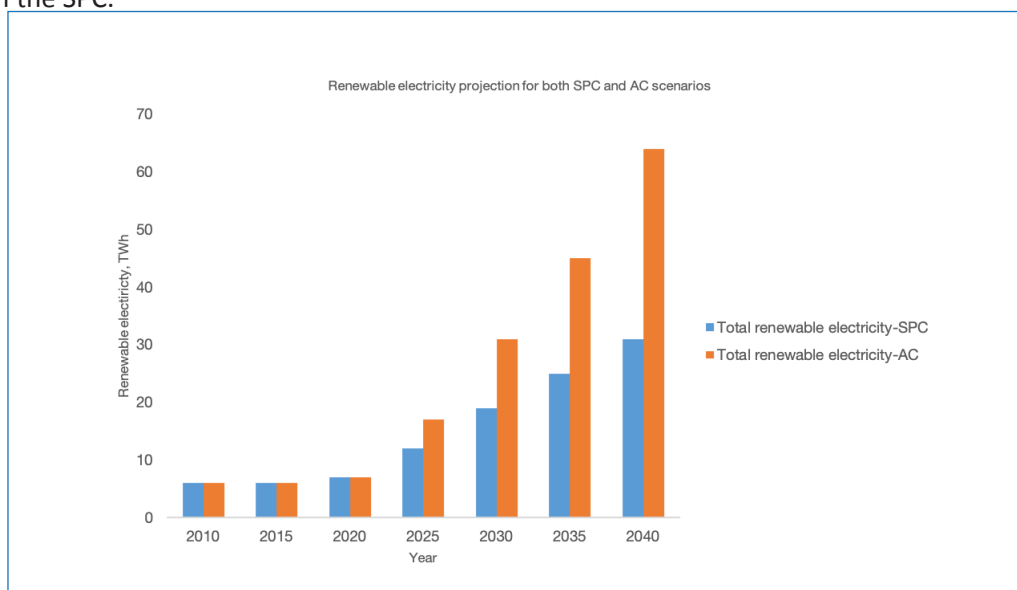


Fig. 8. Role of renewable electricity in the supply mix between 2010 to 2040 under SPC and AC.

## References

- <https://www.energyforgrowth.org/memo/nigerias-electrification-roadmap-after-two-years-where-does-it-stand/>
- [https://energypedia.info/wiki/Nigeria\\_Energy\\_Situation](https://energypedia.info/wiki/Nigeria_Energy_Situation)
- <https://www.ias-potsdam.de/en/blog/2021/09/siemens-nigeria-electrification-roadmap-partnership-after-two-years-where-does-it>
- [https://www.usaid.gov/sites/default/files/documents/1860/Nigeria%20IG\\_2015\\_05\\_03.pdf](https://www.usaid.gov/sites/default/files/documents/1860/Nigeria%20IG_2015_05_03.pdf)
- <https://www.usaid.gov/powerafrica/nigeria>

## CO<sub>2</sub> emissions from electricity production

Nigeria's dependence on gas-powered generators for electricity supply will continue into the foreseeable future as implicated in the previous sections although the share of renewable electricity in the supply mix will creep up till 2040 (18% to 27% depending on the scenario). Thus, there will be associated CO<sub>2</sub> emissions from the electricity supply industry. The electricity carbon intensity has varied between 450 and 488 gCO<sub>2</sub> kWh from 2010 till date. Given that in both the SPC and AC, coal, oil and gas will still play a major role in the electricity supply mix, significant decarbonization of the sector is not expected till about 2060. At this time, the renewable electricity production would have increased to about 111 TWh (SPC) and 394 TWh (AC) if the anticipated growth rates for SPC (0.063 per yr) and AC (0.091 per yr) are upheld. During the recent COP26, Nigeria announced a national policy that will achieve zero GHG emissions target by 2050. Specifically, there will be complete electrification of the economy and increased solar PV utilisation as replacement to gas-powered facilities to facilitate emissions reduction to the zero target.

## References

- <https://rea.gov.ng/the-unveiling-of-nigerias-energy-transition-plan-at-cop26/>

## Energy balance (energy sources to end-uses)

Fig. 9 shows the projected energy sources for the SPC and AC. Consistent with earlier discussion, fossil fuels will continue to be in demand, the TWh rise in renewable electricity is evident from the increased presence of hydro and solar PV particularly from 2030 onwards. Fig. 10 demonstrates that fossil fuels consumption by industrial producers and chemicals manufacturing as well as the transport sector will be a big feature of the future market. The fossil fuels demand in the transport sector could be mitigated by a favourable policy shift towards the electric vehicles since Nigeria is the second largest auto-market on the continent. For example, based on the AC, by 2040 there will be about 37 million vehicles in the country (a 164% increase from the present 14 million vehicles).

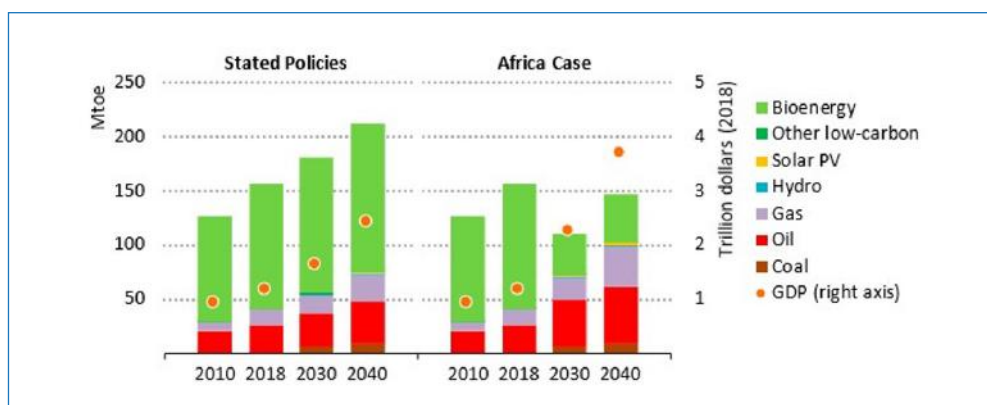
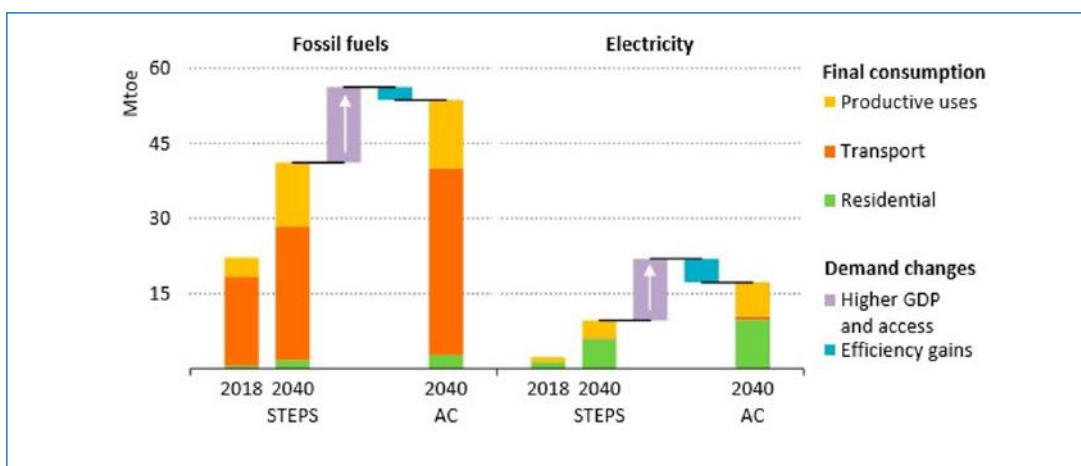


Fig. 9. Primary energy demand trajectory according to SPC and AC scenarios



**Fig. 10.** Expected energy consumption pattern in different sectors of the economy

## References

- <https://www.ashurst.com/en/news-and-insights/legal-updates/nigerias-energy-transition/>
- <https://www.weforum.org/agenda/2020/09/nigeria-using-pandemic-build-sustainable-energy-future/>
- <https://energysustainoc.biomedcentral.com/articles/10.1186/2192-0567-2-15>
- <https://www.iea.org/policies/4974-nigeria-renewable-energy-master-plan>
- <https://www.cnn.com/2021/11/03/business/nigeria-clean-energy-transition/index.html>
- <https://cleanenergynews.ihsmarkit.com/research-analysis/nigerian-government-retains-focus-on-gasbased-transition.html>
- <https://eneken.ieej.or.jp/data/6209.pdf>
- <https://www.tandfonline.com/doi/pdf/10.1080/14693062.2019.1661818?needAccess=true>

## 3. Industry, Buildings, and Agriculture

### 3.1. Food & Agriculture

#### What is the energy balance (energy sources used)? And the GHG intensity, compared to other countries?

The agricultural sector in Nigeria has access to less than 1% of the total energy supply in the country<sup>2</sup>. This is concerning given the exponential rise in total energy demand with population growth over the next three decades under either the Stated Policies Case (SPC) or the Africa Case (AC). Not surprisingly, the agricultural sector does not appear to be a major contributor to the national GHG emissions. According to the IEA database, the principal GHG emitters of the Nigerian economy are the transport, electricity & heat producers, residential and manufacturing sectors. However, with the introduction of the 2013 Agricultural Transformation Agenda, there has been a growing emphasis on farm mechanization and associated GHG emissions from fossil fuels consumption by agricultural machinery and equipment.

#### Are the best available low carbon technologies used/considered? If not, is it an economic problem? A matter of regulation? Or some social issues?

The Federal Ministry of Agriculture and Rural Development (FMARD) has released a “Green Alternative” document that supports the government’s policy towards climate change and environmental sustainability in its efforts to promote agricultural sector productivity. Presently, off-grid solar PV installations, small wind turbines (<50 MW) and continuing construction of small dams in some rural farming communities across the country constitute the only evidence for low-carbon technologies being encouraged by the government. However, more still needs to be done. Better funding and superior management transparency are lacking.

<sup>2</sup> Onyema M-A. C., (2016), International Food Policy Research Institute: Nigeria Strategy Support Program, Policy Note No. 24.

## Is there a roadmap to decrease GHG emissions for 2030 - 2050

### If yes, what are the intermediary steps?

As previously alluded to (cf. *Sec. 1.2.3*), the overall economy has witnessed a 6.4% drop in GHG emissions in the past decade. Even so, the complete decarbonisation of the economy and hence, the food and agricultural industries, is not expected until about 2050 based on the recent government policy (2050 zero GHG emissions target) announced during COP26 in November 2021. As part of the implementation efforts, the Nigerian government is commissioning the 3050 MW Mambilla Hydropower Project in 2030. Among others, the facility will have four dams which will support present irrigation needs, especially in the agriculturally intensive Middle Belt states of Nigeria and also increase the share of renewable electricity supply thereby reducing GHG emissions. Additional installation on solar PV-based mini-grids is also envisioned from 2030 as seen in *Fig. 9*. These benefits and more will have flow-on effect into the agricultural sector of the economy.

## Is the implementation of low-carbon technologies helped by the government?

### For refurbishing or replacing equipment? How are public authorities pushing the transformation? Through benchmarking? Audits?

As indicated in *Sec. 3.2*, the Agricultural Promotion Policy (APP) of the present FMARD has produced the “Green Alternative” document<sup>3</sup>. Although the new policy highlights eleven national priorities, only one of them, “Factoring climate change and environmental sustainability” carries the explicit notion that the policy instrument may engage low-carbon technologies to mitigate GHG emissions as well as land, soil and natural ecosystems for improved agricultural sector productivity. Attitude towards the adoption of low-carbon technologies is driven more by national goals, namely;

- Lifting 100 million people out of poverty and accelerated economic growth
- Bringing modern energy services to the entire population and,
- Managing the long-term job loss in the oil sector that will result from reduced global demand as the world transitions to zero emissions economy

than by international benchmarking.

Nigeria’s commitment to rollout solar powered technologies and end gas flaring seems to be working (a reduction in gas flaring by 70% between 2000 to 2019) albeit slowly. Developments in agricultural mechanization are being spear-headed by nearly 40 government agencies involved with various food and agricultural technologies such as National Agency for Science & Engineering Infrastructure (NASENI) and National Centre for Agricultural Mechanization (NCAM). For example, through collaboration with state governments, agricultural innovations promoting decarbonization are being deployed at NASENI<sup>4</sup>. While government efforts in the implementation of the Agricultural Transformation Agenda (ATA) have been largely fruitful, international benchmarking activities are somewhat diffused. It is also apparent that public authorities are somewhat lethargic in pushing low carbon economic transformation. This may be seen in the Petroleum Industry Act (PIA 2021) which places emphasis on increased prospecting of fossil fuels rather than on renewable energy investments in frontier locations and without targeted emphasis in the Economic Recovery & Growth Plan (2017-2020)<sup>5</sup>.

## Are there incentives for carbon capture, utilisation, and storage? How?

Nigeria’s energy transition program does not indicate explicit incentives for CCUS. However, it has identified a domestic market for CCUS technologies for the mitigation of industrial emissions to facilitate achievement of its 2050 zero target. As a result, the government is partnering with the International Finance Corporation and the World Bank<sup>6</sup>. The initiative involves:

- World Bank collaboration with the government to develop policies and regulations to speed the adoption of CCUS technologies while concurrently assisting the domestic industry to meet international standards.

<sup>3</sup> <https://agra.org/wp-content/uploads/2017/12/agra-nigeria-final.pdf>

<sup>4</sup> <https://naseni.org/>

<sup>5</sup> [https://www.cbn.gov.ng/Out/2017/CCD/Financial%20Inclusion%20Newsletter\\_%20MAY%202017\\_Volume%20%20Issue%202-final%20-%20Review%20%20%20.pdf](https://www.cbn.gov.ng/Out/2017/CCD/Financial%20Inclusion%20Newsletter_%20MAY%202017_Volume%20%20Issue%202-final%20-%20Review%20%20%20.pdf)

<sup>6</sup> <https://pressroom.ifc.org/all/pages/PressDetail.aspx?ID=26819>

- IFC in partnership with the government, will produce a database of key CO<sub>2</sub> emissions sources and possible sites for underground sequestration. This will include identifying the most promising sectors and private companies that can pilot new CCUS technologies.

**If relevant, what about recycling? What percentage is recycled? What are the obstacles to increase recycling? Is a policy to increase recycling already in place or in project?**

A recycling program is under the auspices of the Federal Ministry of Environment, embedded in the department's Clean & Green Initiative. In practice, however, solid waste management (collection, processing and recycling) is often a state affair (there are 36 states in Nigeria). Lagos State, where Africa's largest city, Lagos, is located, runs an enviable recycling program under the agency of the Lagos State Waste Management Authority. The program has become a model for other big cities such as Ibadan, Abuja, Kano and Port-Harcourt. The LAWMA recycle program is decentralized to the 57 local government areas (LGAs) in the state where private recycling companies handle the waste collection, processing and materials recovery. Over 40 million tonnes of waste are produced annually in Nigeria with about 30% of this as recyclable plastics, electronic wastes and other PVC materials. The recycling business is principally organized by the informal sector through social participation (waste pickers subcontracted by private companies). Thus, the absence of a central policy on solid waste management has led to a proliferation of private recycling companies operating with little or no regulation<sup>7</sup>. Despite the central government's relative apathy towards recycling, private Nigerians have developed a niche market for waste-to-wealth technologies as exemplified by young entrepreneurs like Victor Boyle-Komolafe whose company, GIVO, is processing plastic bottles into plastic face shields<sup>8</sup>. By same token, partnership between the Nigeria's National Environmental Standards & Regulation Enforcement Agency, the UN Environment and a private company, Global Environment Facility, has led to the first e-waste processing facility in Nigeria<sup>9</sup>. Other developments are found in public institutions where both recycling and waste valorisation activities are providing parallel revenue streams in the overall waste management arm. With its burgeoning population, continuing advocacy with the Federal government on a robust policy for education on recycling, is essential to avoid a degenerative or even chaotic market environment.

**Are there some case studies or best practices you would like to share?**

In terms of smart technology embrace, development and business practices, the Lagos State Waste Management Authority provides inspiration for the future of sustainable resource harnessing in Nigeria. LAWMA has received both national and international awards for its adventures.

<sup>7</sup> Nzeadibi T.C. & Adama O. (2013), "Improved recycling performance: Policy options for Nigerian cities", The Nordic Africa Institute, Policy Note 2.

<sup>8</sup> <https://www.government.nl/latest/news/2021/04/08/%E2%80%98over-the-next-five-years-we%E2%80%99re-going-to-recycle-150-million-plastic-bottles%E2%80%99>

<sup>9</sup> <https://www.unep.org/news-and-stories/press-release/nigeria-turns-tide-electronic-waste>

## Table of Contents

---

<b>1.</b>	<b>National energy profile 2019</b>	383
<b>2.</b>	<b>Energy perspectives 2030- 2050</b>	386
<b>3.</b>	<b>Building sector</b>	389
3.1.	Existing buildings	389
3.2.	New buildings	390
<b>4.</b>	<b>Industry</b>	391

## 1. National energy profile 2019

### Total yearly consumption: final energy, electricity (TWh)

Year	Energy Consumption (TWh)	Electricity Consumption (TWh)	Elec/Energy (%)
1990	708	126	19.4
1995	802	141	19.4
2000	994	188	21.1
2005	1 185	242	22.7
2010	1 071	245	24.8
2015	925	232	27.4
2019	995	235	25.6

**Table 1.** Total yearly consumption: final energy, electricity (TWh)

<https://www.iea.org/data-and-statistics/data-tables?country=SPAIN&energy=Balances&year=2019>

and: <https://www.iea.org/data-and-statistics/data-browser/?country=SPAIN&fuel=Energy%20consumption&indicator=TotElecCons>

During this period, three major factors regarding the developments in energy and electricity consumption have been: (a) an increase in the population from 38.8 million to 46.9 million (+ 20.9%); (b) a decrease in the share of industry in GDP from 22% to 16%; (c) an increase in energy consumption up to 2005 and a decrease thereafter. The result is a 40.5% increase in final energy consumption over the period 1990-2019.

Concerning electricity, after an increase of around 94,2% between 1990 and 2005, the consumption has stabilised and was slightly decreasing from 2005 to 2019.

As in the other countries, the significant trend is an increase in the ratio of electricity consumption / final energy consumption. However, during the last few years, the trend reversed to some extent. The explanation is probably in an increasing GDP inducing higher fossil energy consumption principally in transport and industry.

### Per capita yearly final energy and electricity consumptions (MWh/person per year)

Year	MWh/person	MWh/person
1990	18.1	3.5
1995	20.2	3.9
2000	24.4	5.1
2005	27.0	6.1
2010	22.8	5.7
2015	19.8	5.4
2019	21.3	5.5

**Table 2.** Per capita yearly final energy and electricity consumptions (MWh/person per year)  
Data from IEA, Key World Energy Statistics, Selected indicators.

Energy consumption and electricity per capita increased up to 2005 and decreased after, following the economic crisis after 2008.

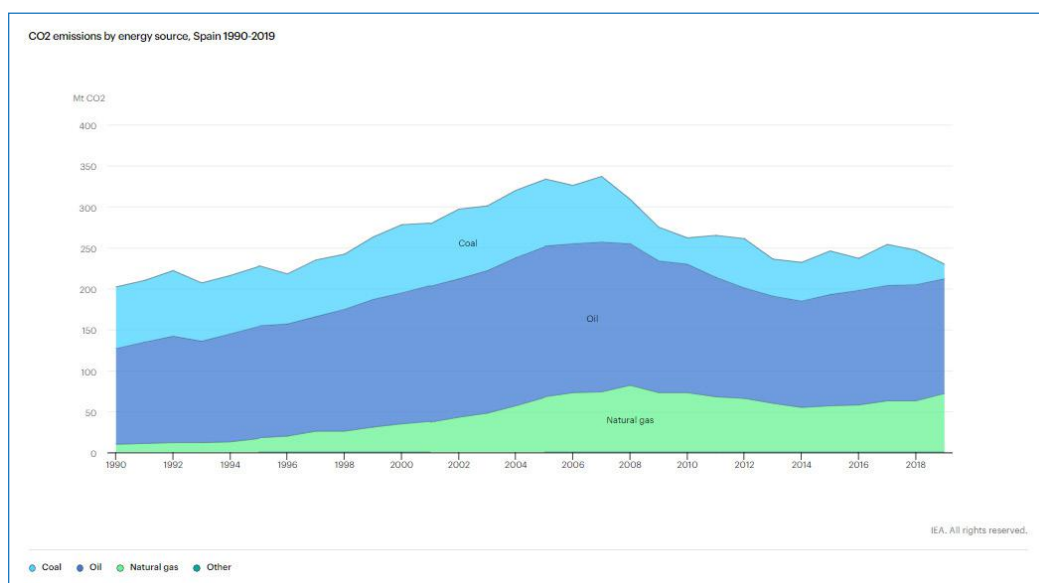
### Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>), total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)

Year	Total CO <sub>2</sub> Emissions (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions from electricity (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions per capita
1990	202.7	66.283	5.2
1995	228.2	60.820	5.8
2000	278.6	98.990	6.9
2005	333.7	118.221	7.6
2010	262.1	72.064	5.6
2015	247.1	82.306	5.3
2019	230.9	54.104	4.9

**Table 3.** Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>), total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)  
 Data from IEA, Data & Statistics <https://www.iea.org/data-and-statistics/data-browser/?country=SPAIN&fuel=CO2%20emissions&indicator=TotCO2>  
 (for 1990-2015)  
 IEA CO<sub>2</sub> emissions from fuel combustion 2019 Highlights (for 1990-2015)  
 IEA Key World Energy Statistics 2019 for 2019 data

The important reduction of emissions after 2005 is the consequence of a decrease in coal consumption on one side and strong increase in renewable energy generation on the other. The emission level per capita follows a similar tendency.

### CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)

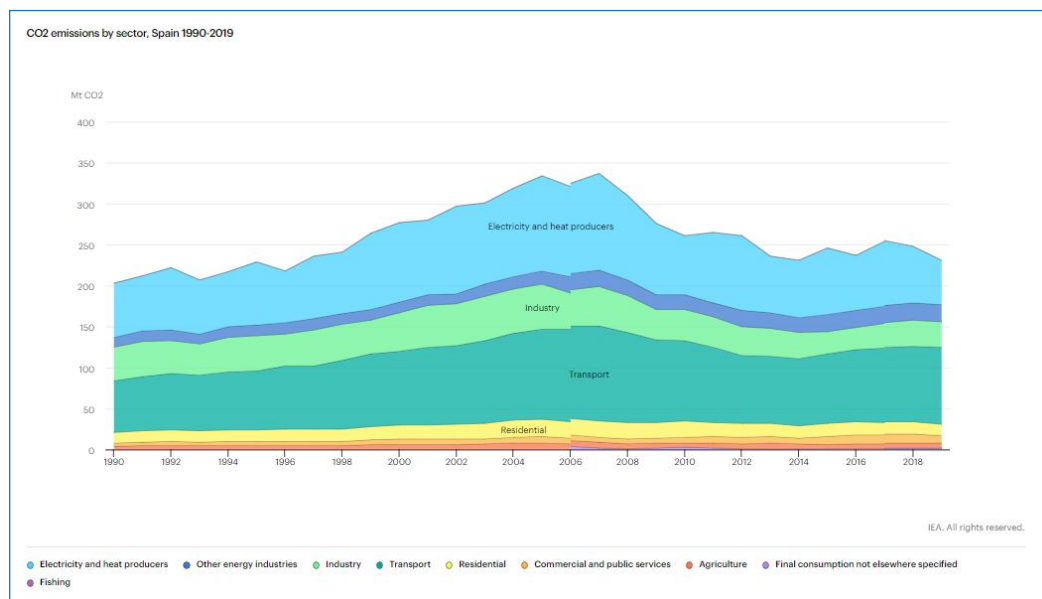


**Fig. 1.** CO<sub>2</sub> emissions by fossil energy source

Data from IEA, Data & Statistics <https://www.iea.org/data-and-statistics/data-browser/?country=SPAIN&fuel=CO2%20emissions&indicator=CO2BySource>

As in many other OECD countries, the use of coal has been strongly reduced since 2005, while the use of oil slightly decreased and the use of natural gas remained stable or slightly decreased after 2010, reaching its minimum level around 2014.

## CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)

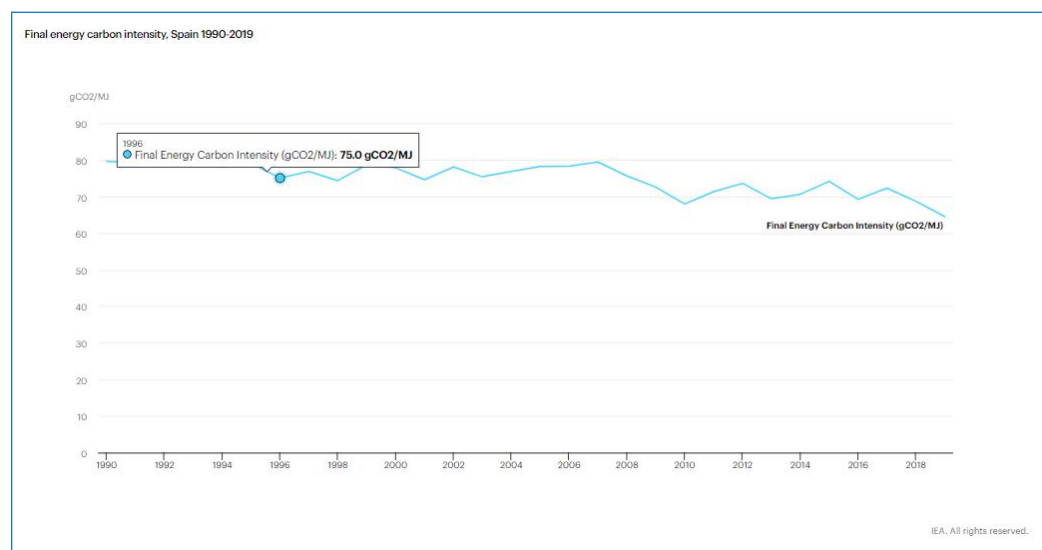


**Fig. 2.** CO<sub>2</sub> emissions by sector

Data from IEA, Data & Statistics <https://www.iea.org/data-and-statistics/data-browser/?country=SPAIN&fuel=CO2%20emissions&indicator=CO2BySector>

Emission from all sectors, except from commercial services and other energy industries, which have slightly increased over the period, have followed similar tendencies: an increase up to 2005/07 and a decrease thereafter.

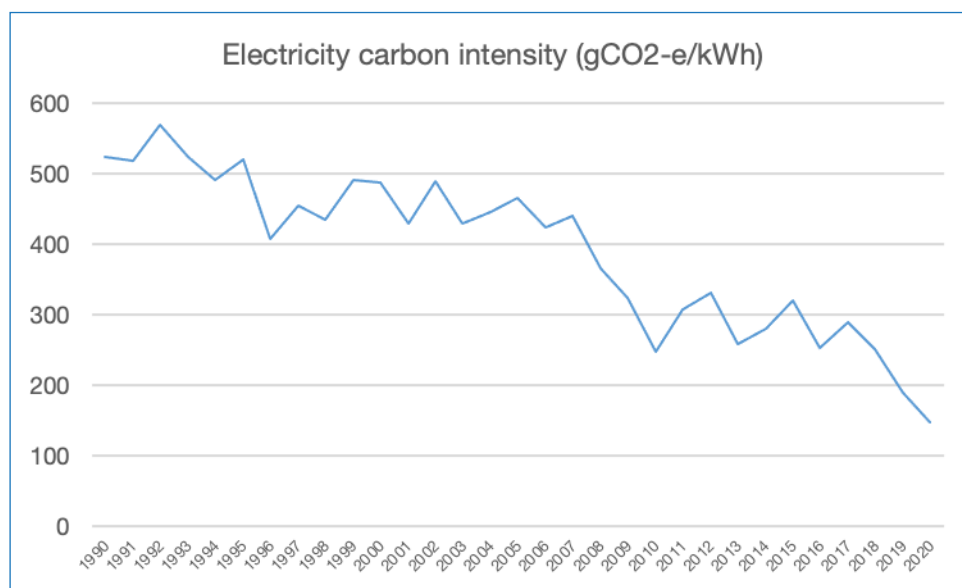
## Final energy carbon intensity: gCO<sub>2</sub>/MJ and gCO<sub>2</sub>/kWh (1 Megajoule = 0.27778 kilowatt hours)



**Fig. 3.** Final energy carbon intensity, Spain 1990-2019

Data from IEA, Data & Statistics <https://www.iea.org/data-and-statistics/data-browser/?country=SPAIN&fuel=CO2%20emissions&indicator=FEI>

## Electricity Carbon intensity: gCO<sub>2</sub>/kWh



**Fig.4.** Electricity Carbon Intensity Spain 1990 - 2020

IEA, Data & Statistics; Instituto para la Diversificación y Ahorro Energético (IDEA): Balance de Energía Final:  
<https://www.iea.org/data-and-statistics/data-browser?country=SPAIN&fuel=CO2%20emissions&indicator=FECL>;  
 Spanish emisión inventory: GHG emissions inventory by gas and sector

Electricity carbon intensity has dropped during the period 1990-2020 because of the reduction in coal-based electric power generation and a strong increase in renewable electricity production.

## 2. Energy perspectives 2030- 2050

The Regulation 2018/1999 adopted by the European Union (EU), requires Member States to implement strategies and measures designed to meet the objectives and targets of the EU for energy and its long-term GHG commitments, in consistency with the Paris Agreement and, from 2021 to 2030, the EU's targets for energy and climate.

Spain, as a member of the EU and according to its regulation, has developed a National Integrated Energy and Climate Plan 2021-2030 (*Plan Nacional Integrado de Energía y Clima (PNIEC) 2020-2030*). This document was later supplemented with the *Long-Term Strategy for a Spanish economy competitive and climatically neutral in 2050*, which develops a roadmap to reach net zero emissions in 2050 with intermediate steps in 2030 and 2040.

Both of the above regulations are included in Law 7/2021 on Climate Change and Energy Transition. This law sets the following emissions reduction, renewable energy and energy efficiency targets for 2030:

- a. reduction of GHG emissions by, at least, 23% with respect to 1990;
- b. reach at least 42% of energy from renewable resources in the final energy consumption;
- c. reach 74% of renewable energy generation in the electricity generation mix;
- d. improve energy efficiency with the aim of reducing primary energy consumption by 39.5% with respect to the baseline.

These regulations include the long-term objective of reaching climate neutrality before 2050, or within the shortest possible timeframe.

**Does your country have national roadmaps regarding energy production and GHG emissions?****What legal status do these documents have? What is their timeline?**

As mentioned above, Law 7/2021 establishes:

- 1) The specific objectives to reach by 2030, which are: a) reduce GHG emissions by 23% with respect to 1990; b) reach a renewable energy penetration in the final energy consumption of, at least, 42%; c) reach an electrical generation mix with, at least, 74% from renewable sources; and d) improve energy efficiency for reducing primary energy consumption by at least 39.5% with respect to the baseline; and
- 2) The obligation to achieve carbon neutrality by 2050,

**Roadmap for the energy mix**

Roadmaps by energy source and use for the reduction of total final energy consumption are included in the table below; a reduction in the use of fossil fuels of 25% for 2030 and 95% for 2050 is anticipated, whereas the non-energy uses of feedstocks (e.g. for petrochemicals) will slightly increase.

	2019	2020	2025	2030	2035	2040	2045	2050
<b>Non energy uses</b>	61.8	61.6	64.0	64.0	64.0	69.8	69.8	69.8
<b>Renewable thermal energies</b>	72.7	69.2	81.4	87.2	104.7	151.2	232.6	279.1
<b>Electricity</b>	234.5	220.9	232.6	238.4	255.9	302.4	314.0	325.6
<b>Fossil energies</b>	694.1	572.5	628.0	523.4	418.7	244.2	127.9	34.9
<b>Total</b>	1 063.2	924.2	1 006.0	913.0	843.2	767.6	744.3	709.4

**Table 4.** Roadmap for the energy mix (TWh)

Renewable thermal energies are Solar thermal, geothermal, biomass, biogas and biowaste.

Ministerio para la Transición Ecológica: Decarbonization Strategy to 2050, Annex E-5: Climate neutrality scenario

**Roadmap for GHG emissions (country)**

The roadmap for national GHG emissions in the present Integrated National Energy and Climate Plan is presented in the following table:

2020	2025	2030	2035	2040	2045	2050
270.9	282.7	222	162	102	56	29

**Table 5.** Roadmap for the GHG emissions (MtCO<sub>2e</sub>)

Ministerio para la Transición Ecológica: Decarbonization Strategy to 2050, Annex E-5: Climate neutrality scenario

**Roadmap for the electricity mix**

Specific data have not yet been developed. However some important milestones of the long-term strategy to 2050 regarding generation capacity have been set, among which are the following.

- Nuclear generation capacity will reach a 60% reduction by 2030 and be completely shut down by 2035.
- Fossil generation capacity will continuously decrease up to 2050, then disappear.
- Electrical storage capacity will grow to 6 GWh in 2030 and by a further 300% in 2050.
- Renewable generation capacity will be doubled by 2030 and experience a fourfold increase by 2050.

## CO<sub>2</sub> emissions from electricity production

Currently, the Spanish electricity generation has an emissions value of 0.15 kgCO<sub>2</sub>/kWh, which is lower than many other EU countries. It is foreseen to steadily decrease up to 2050 when climate neutrality will be achieved

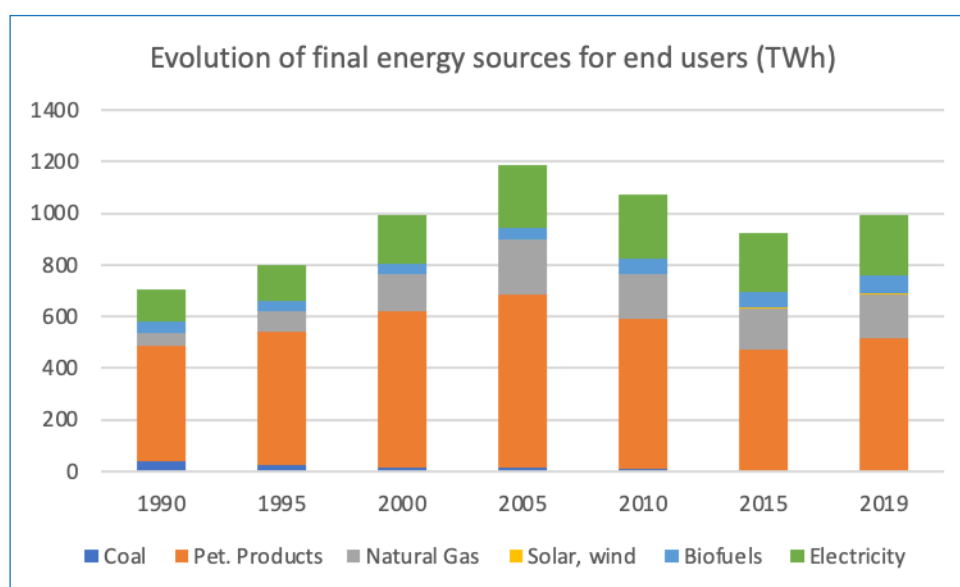
2020	2025	2030	2035	2040	2045	2050
32.5	27	21	11	7	1	0

**Table 6.** Roadmap for the GHG emissions of the electricity sector (MtCO<sub>2e</sub>)

Ministerio para la Transición Ecológica: Decarbonization Strategy to 2050, Annex E-5: Climate neutrality scenario

## Energy balance (energy sources to end-uses)

Final energy consumption reached its peak in 2005. It decreased thereafter until 2015 and from there remained almost stable with a slight increase in 2019.



**Fig. 5.** Evolution of final energy sources for end users (TWh)

<https://www.iea.org/data-and-statistics/data-browser/?country=SPAIN&fuel=Energy%20consumption&indicator=TotElecCons>

### 3. Building sector

#### 3.1. Existing buildings

##### Energy balance 2019 (energy sources to end-uses)

Electricity, natural gas and petroleum products are the major energies in both commercial and household sectors. The share of renewable energy (eg.solar thermal, biomass and some geothermal; wind and solar PV are in electricity) is increasing and, in the household sector, it has reached a level similar to that of petroleum products (*Table 7.*)<sup>1</sup>.

	Commercial and public services	Households
Coal		64.92
Petroleum Products	1 248.72	2 397.48
Natural gas	2 322.83	3 009.24
Non renewable wastes	4.80	
Renewable energies	667.85	2 833.52
Electricity	6 416.72	6 275.27
<b>Total</b>	<b>10 660.91</b>	<b>14 580.44</b>

*Table 7.* Existing Buildings: energy balance (2019) (ktoe)

1 ktoe = 0.01163 TWh, 10 661 ktoe = 124 TWh, 14 580 ktoe = 170 TWh)

##### Energy partition between single houses, apartment buildings and office buildings

*Table 7.* shows energy partition between households (houses and apartment buildings) and commercial buildings, which include office buildings. There is no other segregation by energy consumption.

##### Which systems are mostly used for heating?

Local systems: mainly boilers and electric heating, and, to a lesser extent, heat pumps, solar thermal panels, geothermal systems, etc.

##### Which systems are mostly used for cooling?

Local systems.

##### What are the main choices of the national policy – if there is one – to reduce the emissions from the existing stock of buildings? – to make this reduction affordable?

Buildings renovation to increase efficiency and making it affordable by public subsidies

- *From a technological point of view? (Insulation, heat pumps, low CO<sub>2</sub> district network, geothermal systems, local PV production, etc.).*

Insulation improvement, replacing old boilers with new more efficient ones, installing thermal and PV solar panels for auto- and small-scale consumption, replacing solid and liquid fuels with natural gas and heat pumps

- *From a regulatory point of view? Through land ownership regulations?*

Through regulations on energy performance in buildings, according to the EU directive 2018/844 amending directives 2010/31<sup>2</sup> on energy performance of buildings and directive 2012/27<sup>3</sup> on energy efficiency. This directive reinforces the establishment of long-term renovation strategies by the EU countries to support the renovation of existing buildings in order to transform them to near zero energy buildings. The directive has been transposed into Spanish legislation by Royal Decree (RD) 390/2021.

<sup>1</sup> Eurostat: [https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg\\_bal\\_c&lang=en](https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_bal_c&lang=en)

<sup>2</sup> <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031&from=EN>

<sup>3</sup> <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0027&from=EN>

- *Through subsidies, different financial mechanisms? Which are the priorities: reducing CO<sub>2</sub> or energy; Better inclusivity.*  
Subsidies to reduce energy consumption.
- *Replacing parts of the existing stock of buildings?*  
No.
- *Is there a specific roadmap for this subject?*  
Reducing energy consumption by: a) renovating the thermal installations of 300 000 homes/year; and b) improving the thermal envelope of 120 000 homes/year, from 2020 to 2030.

### **Is there some roadmap for making existing cities more sustainable?**

According to Law 7/2021 on Climate Change and Energy Transition, municipalities with more than 50 000 inhabitants shall develop sustainable urban mobility plans aimed at reducing emissions resulting from mobility. These shall include:

- the setting of low emission zones within the cities before 2023;
- measures to improve and promote public transport;
- measures for the electrification of the public transport network;
- measures to promote the use of private electrical transport means including recharging points;
- the promotion of electrical car-sharing mobility;
- measures aimed at promoting sustainable means of distributing goods.

### **Are there some case studies or best practices you would like to share?**

-

## **3.2. New buildings**

### **Does your country have a national policy regarding new buildings?**

#### **If yes, what are the priorities? (For housing and for office buildings)**

Yes: a) RD 314/2006, Technical Building Code <sup>4</sup>, establishes the basic requirements with which new buildings shall comply, and b) RD 178/2021, Regulation on the Thermal Installations of Buildings<sup>5</sup>.

### **Are some technologies prioritised, in particular for heating and cooling? At the building level?**

#### **At the infrastructure level? (developing district networks, prohibiting connection to the gas network...)**

Energy supply by renewables and electrification are regarded as the main tools for the decarbonisation of the building sector

### **How are they supported? Through regulations? Subsidies?**

Both regulations and subsidies: a) regulation, by the modification of the technical building code (RD 732/2019); and b) subsidies, expected from the Next Generation EU fund.

### **Are there some recommendations and regulations for sustainable districts and cities?**

-

### **Are there some case studies or best practices you would like to share?**

-

<sup>4</sup> <https://boe.es/buscar/pdf/2006/BOE-A-2006-5515-consolidado.pdf>

<sup>5</sup> <https://www.boe.es/eli/es/rd/2021/03/23/178/dof/spa/pdf>

## 4. Industry

Three sectors of industry are considered below:

- Iron and Steel industry (including mining),
- Oil & Gas industry,
- hemical industry (in particular petrochemicals: ammonia, ethylene, plastic...)

**What is the energy balance (energy sources used)?  
And the GHG intensity, compared to other countries?**

### Energy balances (2019)<sup>6</sup>

Fossil fuels, especially petroleum products and natural gas and electricity are the main energies in all three sectors; renewable energies has not been playing an important role so far.

#### a) Chemical industry

Natural gas is the main energy supply in the chemical industry, coal and coke are used in carbochemical plants

	Chemical & petrochemical
Coal and Coke	121.63
Petroleum Products	81.47
Natural Gas	2 593.14
Renewable energy	5.91
Electricity	790.63
<b>Total</b>	<b>3 592.78</b>

**Table 8.** Energy balance of Chemical sector (ktoe/year  
(1ktoe = 0.01163 TWh, 3593 ktOE = 41.8 TWh))

#### b) Steel industry

Coal and coke are used in blast furnaces, which account for about 25% of steel production

	Iron and Steel	Mining and quarrying*
Coal and Coke	77.28	
Blast furnace and coke oven gases	72.95	
Petroleum Products	79.33	145.94
Natural Gas	574.40	158.02
Renewable energy	0.03	0.94
Electricity	1 141.36	176.78
<b>Total</b>	<b>1 945.35</b>	<b>481.68</b>

**Table 9.** Energy balance of Steel industry (including Mining) (ktOE/year)  
(1945 ktOE = 22.6 TWh, 482 ktOE = 5.6 TWh)

\* Includes mining activities of other metallic ores

<sup>6</sup> Source of data: Eurostat; <https://ec.europa.eu/eurostat/web/main/data/database>

**c) Oil industry**

Petroleum products include residual fuels and refinery off gases that are produced during the refining processes.

	Oil refining*
Coal and Coke	
Petroleum Products	4 719.212
Natural Gas	2 775.559
Renewable energy	
Electricity	355.546
<b>Total</b>	<b>7 850.32</b>

**Table 10.** Energy balance of Oil industry (ktoe/year)  
(7 851 ktoe = 91.3 TWh)

\* Petroleum products include 4552 ktoe of refinery fuel gas

**GHG emissions and emission intensity**

Emission intensities, calculated with respect to the production value, are similar to those of other countries (see *Tables 11, 12, 13*)

**a) Chemical industry**

	Chemical & petrochemical
GHG emissions from energy (ktCO <sub>2</sub> -e)	9 645.66
GHG emission intensity (tCO <sub>2</sub> -e/M€)	236.48

**Table 11.** Chemical Industry, GHG emissions and emission intensity

**b) Steel industry**

	Iron and Steel
GHG emissions from energy (ktCO <sub>2</sub> -e)	5 649.91
GHG emission intensity (tCO <sub>2</sub> -e/M€)	426.56

**Table 12.** Steel Industry, GHG emissions and emission intensity

**c) Oil industry**

	Oil refining
GHG emissions from energy (ktCO <sub>2</sub> -e)	11 053.02
GHG emission intensity (tCO <sub>2</sub> -e/M€)	289.91

**Table 13.** Oil industry, GHG emissions and emission intensity

**Are the best available low carbon technologies used / considered?****If not, is it an economic problem? A matter of regulation? Or some social issues?**

In the European Union, according to the directive 2008/1/EC (the IPPC Directive), amended by directive 2010/75/EC, all installations of these sectors must implement Best Available Techniques (BAT) to minimise their impact on the environment.

Both directives have been transposed into the Spanish legislation; therefore BATs have been considered and implemented in all aspects related to energy and pollutant emissions.

**Is there a roadmap to decrease GHG emissions for 2030 - 2050****If yes, what are the intermediary steps?**

As discussed above, Section 1, there is a long-term roadmap to 2050 that fosters the reduction / elimination of GHG emissions from 2020 up to 2050, with 2030 as an intermediate step. It then foresees reaching net-zero emissions in 2050 for those sectors, although there are no specific figures for intermediate steps.

**Is the implementation of low-carbon technologies helped by the government? For refurbishing or replacing equipment? How are public authorities pushing the transformation?****Through benchmarking? Audits?**

The EU promotes the implementation of low carbon technologies through a carbon pricing mechanism, which has allowed to create a carbon emissions market for the whole EU: the EU Emissions Trading System (EU ETS); all three sectors covered in this questionnaire response are mandatorily subjected to the system. The mechanism works under the cap-and-trade system by which a cap is set on the amount of greenhouse gases that can be emitted by the installations covered by the system. The cap is then reduced over time and so is the amount of emission permissions in the market. This flexible system promotes investment in low-carbon technologies when carbon costs exceed investment costs in such technologies.

**Are there incentives for carbon capture, utilisation, and storage? How?**

Carbon pricing through the EU ETS system acts as an incentive to promote carbon capture and storage (CCS); so far, it was only used in connection with a power station operating via coal gasification.

There are no other incentives for the moment, although the recently created Next Generation EU Fund could support the development of carbon capture projects, especially in hydrogen production plants.

**If relevant, what about recycling? What percentage is recycled? What are the obstacles to increasing recycling? Is a policy to increase recycling already in place or projected?**

In 2020, Spain adopted the 'Circular Economy Strategy' *España Circular 2030* which sets objectives for this decade, aligned with those of the European Action Plans, and aims, among others, reducing the national consumption of materials by 30%, improving the efficiency of water use by 10%, and cut waste generation by 15%, with respect to 2010. This will allow the GHG emissions from the waste sector to be below 10 million tonnes in 2030 (it was 13.5 in 2018).

Recycling is specifically important for chemicals, although there are no specific figures for it. Regarding steel, about 70% of production comes from scrap material. Recycling is much less important in the case of oil products.

## Table of Contents

---

1.	National energy profile 2019 .....	395
2.	Energy perspectives 2030 - 2050 .....	401

Answer from the Royal Swedish Academy of Engineering Sciences (IVA).

Experts from authorities, industrial organisations and members of the IVA Academy have contributed to answering the questionnaire. The compilation has been made by Lennart Fredenberg, Member of the Royal Swedish Academy of Engineering Sciences (IVA)<sup>1</sup>.

## 1. National energy profile 2019

### Total yearly consumption: final energy, electricity (TWh)

Year	Energy Consumption (TWh)	Electricity Consumption (TWh)	Elec/Energy (%)
1990	373.5	135.5	36.3
1995	416.4	136.6	32.8
2000	410.5	139.1	33.9
2005	398.5	139.3	35.0
2010	404.5	140.1	34.6
2015	375.2	132.5	35.3
2019	377.5	131.4	34.8

**Table 1.** Total yearly consumption: final energy, electricity (TWh)

<https://www.iea.org/data-and-statistics/data-tables?country=SWEDEN&energy=Balances&year=2019>

and: <https://www.iea.org/data-and-statistics/data-browser/?country=SWEDEN&fuel=Energy%20consumption&indicator=TotElecCons>

In the 2010s, total final energy consumption was still at a relatively steady level but decreased slightly. In both the housing and service sectors and the industrial sector, energy consumption remained at about the same level for a long period, although in the industrial sector, energy consumption fell slightly between 2010 and 2019. In the short term, the use of energy in residential and service towers is mainly affected by outdoor temperature, as a large part of it goes to heating. In the transport sector, energy use generally decreased in the 2010s, following the sharp increase it had been experiencing since the 1970s. Decrease in recent years is mainly due to improved energy efficiency in the sector, including through more energy-efficient vehicles.

Electricity use has been declining despite an increasing population. Since the beginning of the 2000s, the trend in electricity use has been slightly decreasing, although its level slightly varied over the years. Since 1990, the Swedish population has increased by more than 1.6 million. Just over half of the electricity is used in the housing and service sectors, followed by industry.

Another factor is the outdoor temperature as a large part of heating in Sweden, almost half of it, is based on electricity. Population changes and the development of energy prices are additional factors that affect the use of electricity.

<sup>1</sup> [lennart.fredenberg@telia.com](mailto:lennart.fredenberg@telia.com)

## Per capita yearly final energy and electricity consumptions (MWh)

Year	Inhabitants (per million)	Energy Consumption (TWh)	Energy Consump- tion per person and per year (MWh)	Electricity Consumption (TWh)	Electricity Consumption per person and per year (MWh)
1990	8.6	373.5	43.4	135.5	15.8
1995	8.8	416.4	47.3	136.6	15.5
2000	8.9	410.5	46.1	139.1	15.6
2005	9.0	398.5	44.3	139.3	15.5
2010	9.4	404.5	43.0	140.1	14.9
2015	9.8	375.2	38.3	132.5	13.5
2019	10.0	377.5	37.7	131.4	13.1

**Table 2.** Per capita yearly final energy and electricity consumptions (MWh)  
Data from IEA, Key world energy statistics, Selected indicators.

Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>),  
total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)

Year	Total CO <sub>2</sub> Emissions (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions from electricity (MtCO <sub>2</sub> )	CO <sub>2</sub> emissions per capita
1990	52.1	1.6	6.1
1995	56.9	3.3	6.5
2000	52.0	3.5	5.9
2005	48.9	3.0	5.4
2010	46.8	3.9	5.0
2015	37.7	1.6	3.8
2019	33.7	2.0	3.1

**Table 3.** Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>), total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)

Tables are based and/or calculated from the following data

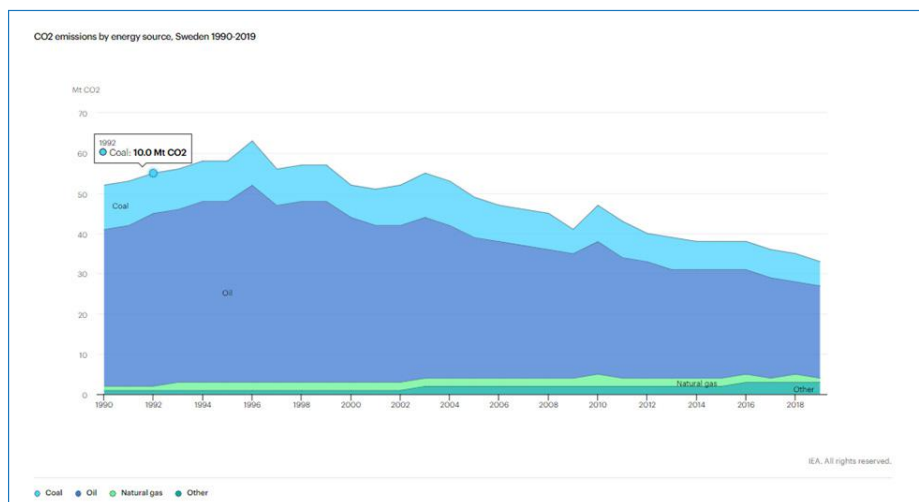
International Energy Agency - Data and statistics -Explore energy data by category, indicator, country or region

IEA (2021) Emission Factors ([https://www.iea.org/t\\_c/termsandconditions/](https://www.iea.org/t_c/termsandconditions/))

<https://www.worldometers.info/world-population/population-by-country/>

The main decrease occurred in the period 2003-2014. The largest contributions to the emission reduction since 1990 result from heating homes and premises and, in recent years, from industry and domestic transport.

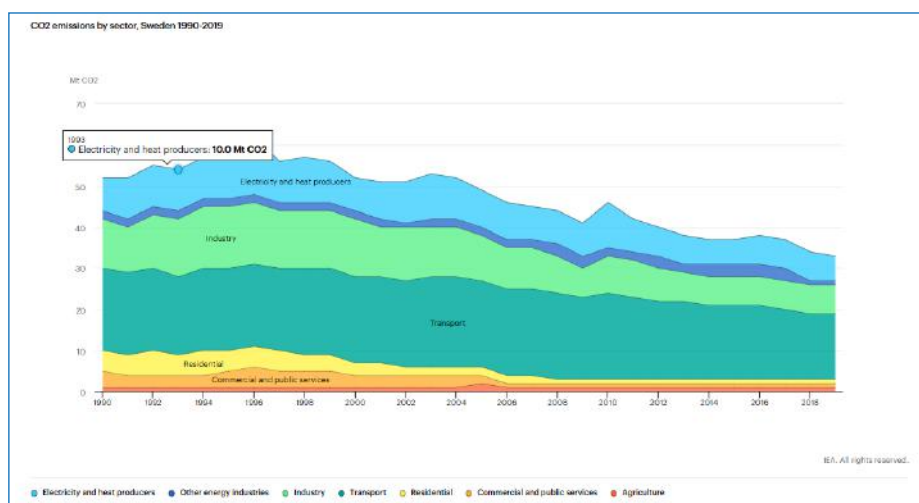
## CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)



**Fig. 1.** CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)

<https://www.iea.org/data-and-statistics/data-browser?country=SWEDEN&fuel=CO2%20emissions&indicator=CO2BySource>

## CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)



**Fig. 2.** CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)

Data from IEA, Data & Statistics

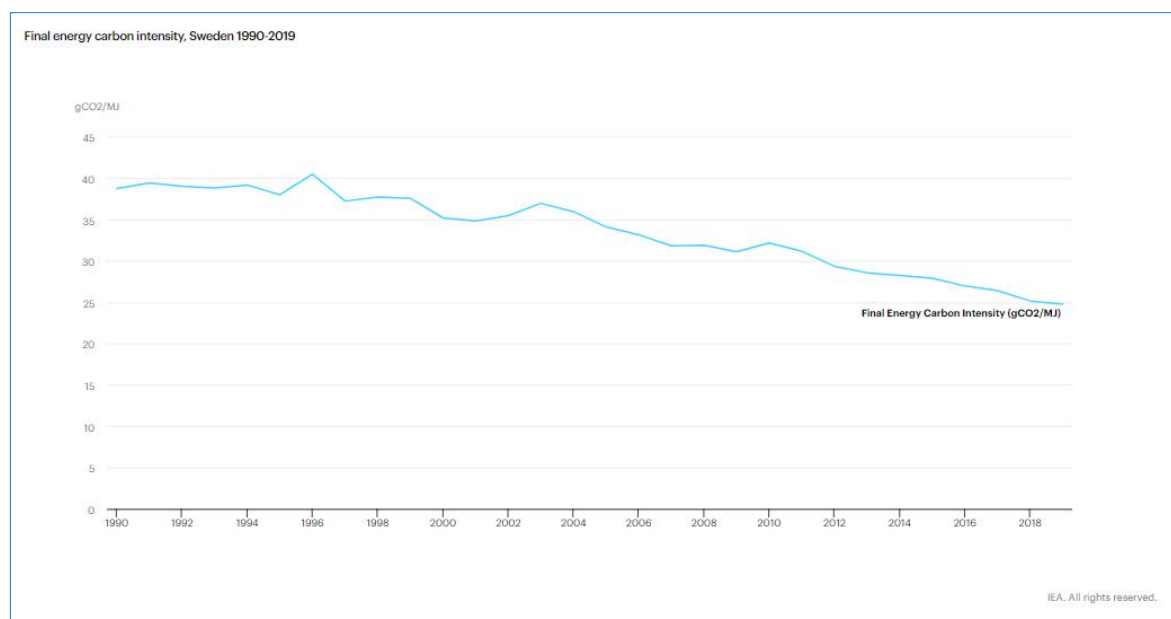
<https://www.iea.org/data-and-statistics/data-browser?country=SWEDEN&fuel=CO2%20emissions&indicator=CO2BySector>

The emission reduction in the heating of homes and premises, residential uses, and commercial and public services, as well as electricity production and district heating, is largely a result of policy instruments and measures, such as investments in infrastructure for district heating, taxes on energy and carbon dioxide emissions, support for the installation of heat pumps and the electricity certificate programme that promotes the production of renewable electricity.

The reduction in emissions from domestic transport may largely be explained by the increasing use of biodiesel and biofuels, both through the declining use of fossil diesel and the increased share of pure biodiesel. Substituting new, more energy-efficient passenger cars for older vehicles also helped to reduce emissions. At the same time, mobile work increased during the period, which had a dampening effect on emission reduction.

Total emissions from the industry varied since 1990. To a large extent, such variations are due to fluctuations in production volumes linked to the economic cycles. Emissions from the industry then stabilised in the early 2000s despite a continued economic upturn in many industries. The decrease since 2006 is mainly due to changes in fuel use and reduced production volumes, as well as ongoing energy efficiency measures.

### Final energy carbon intensity: $\text{gCO}_2/\text{MJ}$ and $\text{gCO}_2/\text{kWh}$ (1 Megajoule = 0.27778 Kilowatt hours)

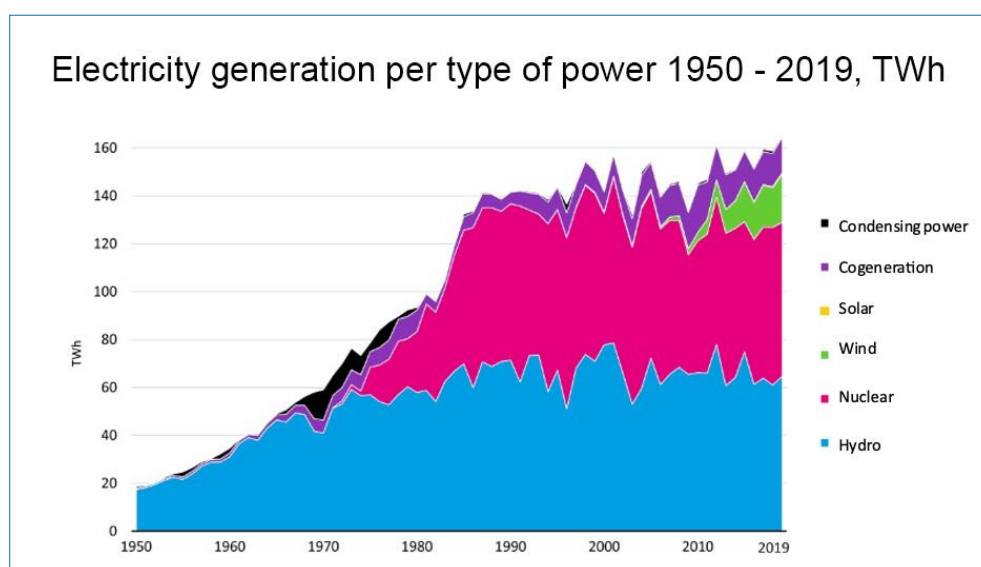


**Fig. 3.** Final energy carbon intensity  
<https://www.iea.org/data-and-statistics/data-browser?country=SWEDEN&fuel=CO2%20emissions&indicator=FECI>

Since around 1985, energy supply has been relatively constant. Despite this, carbon intensity has been steadily falling. The main reasons include the increasing use of biofuels and electricity and district heating. The supply of biofuels has tripled over the last 40 years. During the same time span, the supply of crude oil and petroleum products has considerably decreased. The main reason for it is that residential buildings and facilities are rarely heated using petroleum today. From mid-1975, almost every new built one-family house was equipped with direct electricity heating. This happened during the introduction of nuclear electricity generation.

### Electricity Carbon intensity: $\text{gCO}_2/\text{kWh}$

Swedish electricity production is currently 98% free of fossil fuels. Total generation in 2020 was 161 TWh (hydro 44%, nuclear 30%, wind 17%, cogeneration 8% - mostly bioenergy).



**Fig. 4.** Electricity generation per type of power  
 Source: Sweden Energy Agency – Fact and Figures (Statistics ([energimyndigheten.se](https://energimyndigheten.se)))

The dramatic increase in Swedish electricity production and usage from around 1970 to 1990 coincided with the introduction of nuclear power substituting for fossil fuel-fired condensing power plants. The increase in cogeneration for district heating is also mainly fossil-free, as biomass and waste constitute the fuel supply. Over the last 10 years, the share of wind power has substantially been growing while nuclear power plants have successively been shut down.

### Overview of Sweden's energy supply and use

The Swedish official energy statistics are published by The Swedish Energy Agency. The latest data collected has been published in *Energy in Sweden 2021* - an overview, now available<sup>2</sup>. In Sweden, we use domestic renewable energy sources such as water, wind, the sun and biofuels. We also import nuclear fuels, biofuels and fossil fuels such as oil and natural gas. The energy system in Sweden may be categorised as supply-side and consumption-side. The following diagram illustrates energy system flows in 2019.

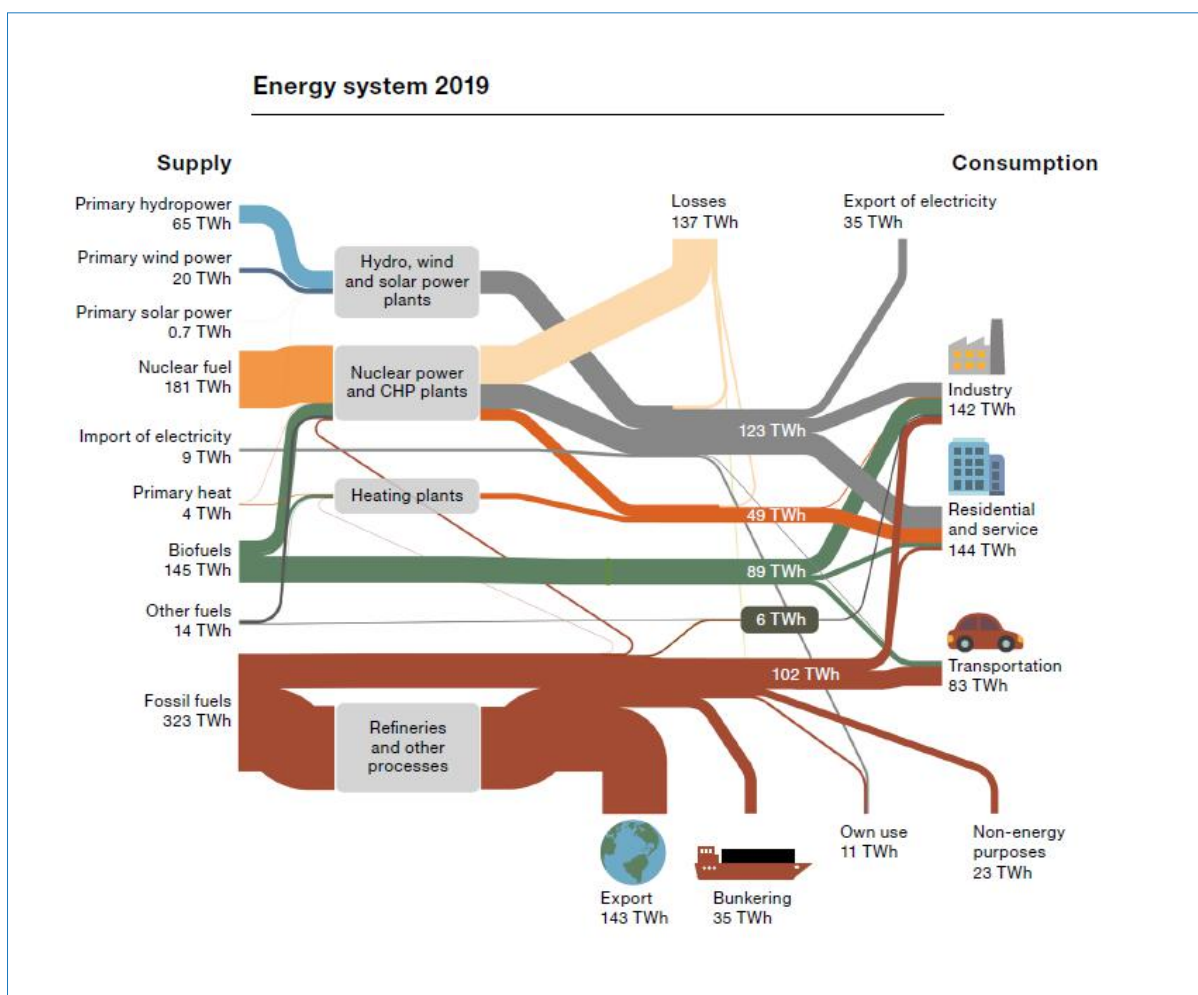


Fig. 5. Energy Systems 2019

<sup>2</sup> <https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=198022>

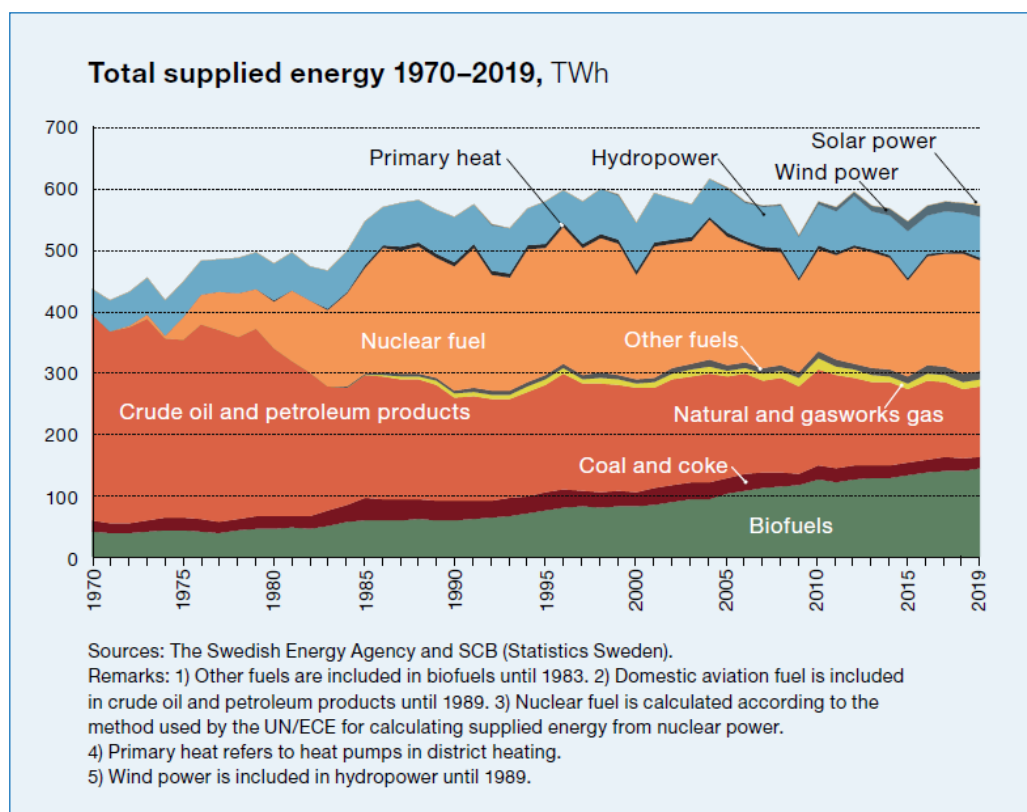


Fig. 6. Total energy supply by energy carrier

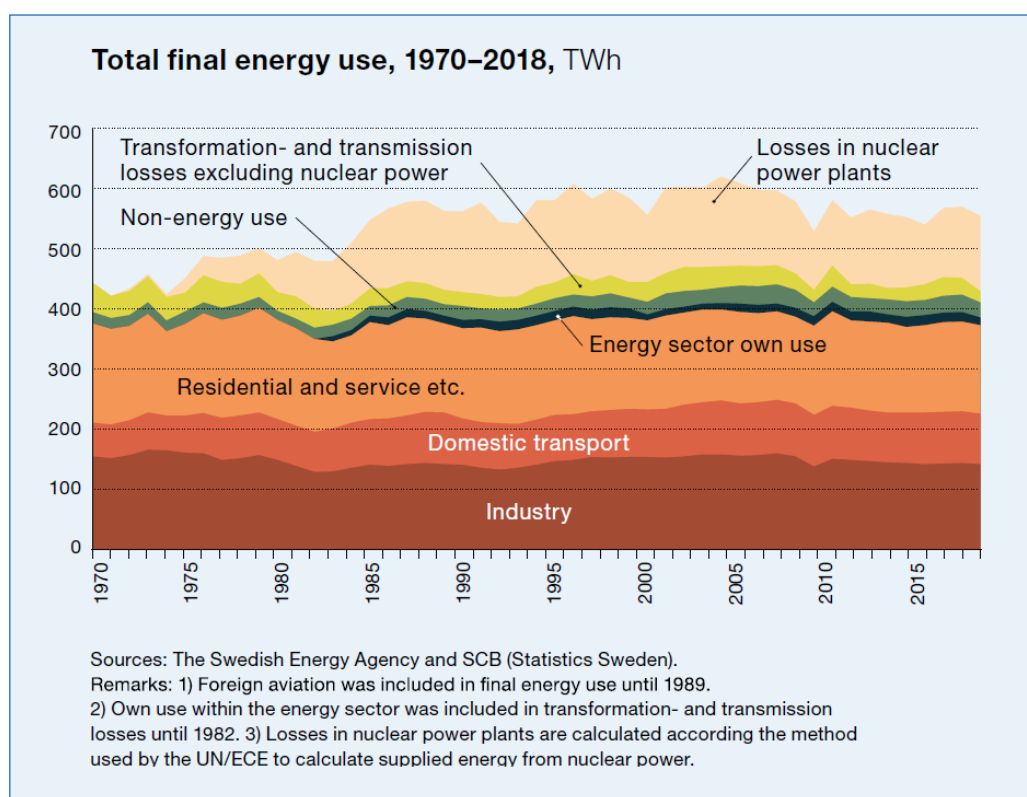
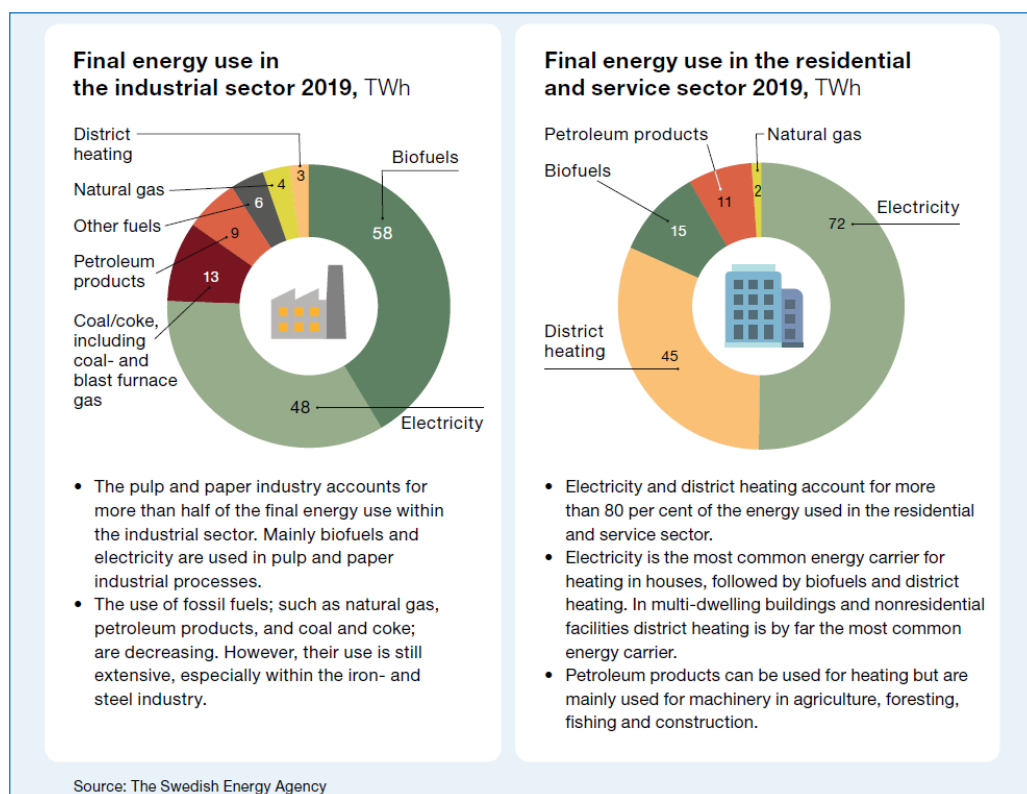


Fig. 7. Total energy use in different sectors



**Fig. 8.** Final energy use in industrial (left) and residential and service (right) sectors

## 2. Energy perspectives 2030 - 2050

If possible, give the national perspectives for 2030 and 2050 or the roadmap to 2030 and 2050 if they exist.

### Does your country have national roadmaps regarding energy production and GHG emissions? What legal status do these documents have? What is their timeline?

In 2017, Sweden adopted a new climate policy framework. It consists of a climate act, climate targets and a climate policy council. Sweden's long-term target is net zero greenhouse gas emissions by 2045 at the latest. **The framework was adopted by the Parliament with a broad majority of the political parties<sup>3</sup>.**

The long-term target for Sweden is net zero greenhouse gas emissions by 2045 at the latest. After 2045, Sweden is to achieve negative net emissions.

### Roadmap for the energy mix

The share of renewable energy shall be at least 50% of total energy consumption by 2020.

### Roadmap for the GHG emissions (country, per capita)

Specific targets are set for the non-EU-ETS<sup>4</sup> sectors:

- By 2020, emissions are to be 40% lower than in 1990
- By 2030, emissions are to be 63% lower than in 1990
- By 2040, emissions are to be 75% lower than in 1990

### Roadmap for the electricity mix

100% of electricity production shall be from renewable sources by 2040. This is however not a cut-off date for banning nuclear power.

<sup>3</sup> Source: the-swedish-climate-policy-framework.pdf (government.se)

<sup>4</sup> EU Emissions Trading System

**Energy balance (energy sources to end-uses)** – see also *Electricity Carbon intensity: gCO<sub>2</sub>/kWh*, page 398

- By 2020, energy consumption shall be 20% more efficient than in 2008;
  - the share of renewable energy shall be at least 50% of total energy consumption;
  - the share of renewable energy in the transport sector shall be at least 10%.
- Moreover, by 2030, energy consumption shall be 50% more efficient than in 2005, expressed as primary energy vs. GDP.

## Table of Contents

---

<b>1.</b>	<b>National energy profile 2019</b>	404
<b>2.</b>	<b>Energy perspectives 2030 - 2050</b>	407
<b>3.</b>	<b>Building sector</b>	411
3.1.	Existing buildings	411
3.2.	New buildings	414
<b>4.</b>	<b>Industry and Agriculture</b>	415
4.1.	Cement industry	415
4.2.	Chemical Industry	418
4.3.	ICT	420
4.4.	Agriculture	421

## 1. National energy profile 2019

In this report, the indicators for the national energy profiles (GHG emissions, energy mix, electricity mix, energy sources to end-uses) are based on figures from the IEA database.

Year	Energy Consumption (TWh)	Electricity Consumption (TWh)	Elec/Energy (%)
1990	204.7	50.0	24.4
1995	216.6	51.3	23.7
2000	224.1	56.4	25.2
2005	236.0	61.8	26.2
2010	239.1	64.0	26.8
2015	216.5	62.1	28.7
2019	210.7	63.1	30.0

**Table 1.** Total annual consumption: final energy, electricity (TWh)

During this period, three main factors in the evolution have been: (a) an increase of the population from 6.7 million to 8.6 million (+ 28.4%); (b) a decrease in the manufacturing industry; (c) progress in energy efficiency measures. There was a peak in energy consumption around 2010 and a slow decline down to 2019. The result is an overall increase of 3% in final energy consumption over the period 1990-2019.

Electricity consumption increased by 26 per cent between 1990 and 2019, however electricity consumption per person and per year peaked around 2005 and returned to 1995 levels in 2019.

The ratio of electricity consumption to final energy consumption increased continuously, to a value of 30% in 2019.

Year	Inhabitants (per million)	Energy Consumption (TWh)	Energy Consumption per person and per year (MWh)	Electricity Consumption (TWh)	Electricity Consumption per person and per year (MWh)
1990	6.7	204.7	30.6	50.0	7.5
1995	7.0	216.6	30.1	51.3	7.3
2000	7.1	224.1	31.6	56.4	7.9
2005	7.4	236.0	31.9	61.8	8.3
2010	7.8	239.1	30.7	64.0	8.2
2015	8.3	216.5	26.1	62.1	7.5
2019	8.6	210.7	25.5	63.1	7.3

**Table 2.** Total annual consumption per capita: final energy, electricity (MWh per capita per year)

Tables are based and / or calculated from the following data:

International Energy Agency - Data and statistics -Explore energy data by category, indicator, country or region

IEA (2021) Emission Factors ([https://www.iea.org/t\\_c/termsandconditions/](https://www.iea.org/t_c/termsandconditions/))

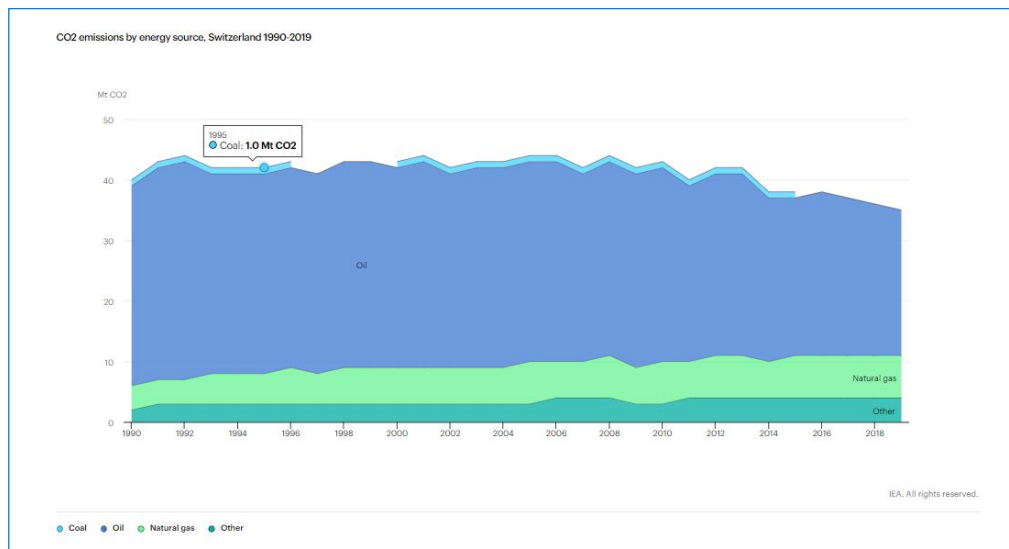
<https://www.worldometers.info/world-population/population-by-country/>.

Year	Total CO <sub>2</sub> Emissions (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions from electricity (MtCO <sub>2</sub> )	CO <sub>2</sub> emissions per capita
1990	40.8	1.0	6.0
1995	41.5	1.3	5.8
2000	42.0	1.5	5.8
2005	44.0	1.7	5.9
2010	43.3	1.6	5.5
2015	37.4	1.6	4.5
2019	35.6	1.8	4.2

**Table 3.** Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>), total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)

The significant reductions in CO<sub>2</sub> emissions over the last 20 years are both a consequence of the decrease in industrial activities in Switzerland on one side and of measures to improve energy efficiency. The emissions level per capita is low compared to many other industrialised countries since the electricity production mix is largely decarbonised due to a big share of nuclear and hydraulic generation.

### CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)



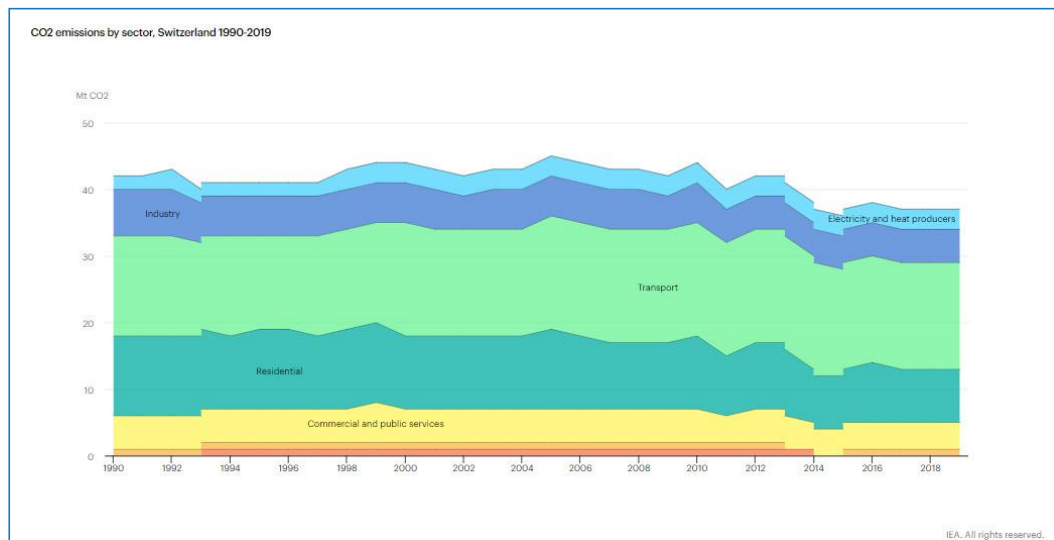
**Fig. 1.** CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)

Data from IEA, Data & Statistics

<https://www.iea.org/data-and-statistics/data-browser?country=SWITLAND&fuel=CO2%20emissions&indicator=CO2BySource>

The share of power generation based on fossil fuels (oil and gas based) is very low in Switzerland. Coal is not used for this application. Fossil fuels are mainly used for heating, industry and mobility. The use of oil is slightly decreasing as heating is moved to heat pumps and other non-fossil sources, but the use of natural gas has been slightly increasing.

## CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)



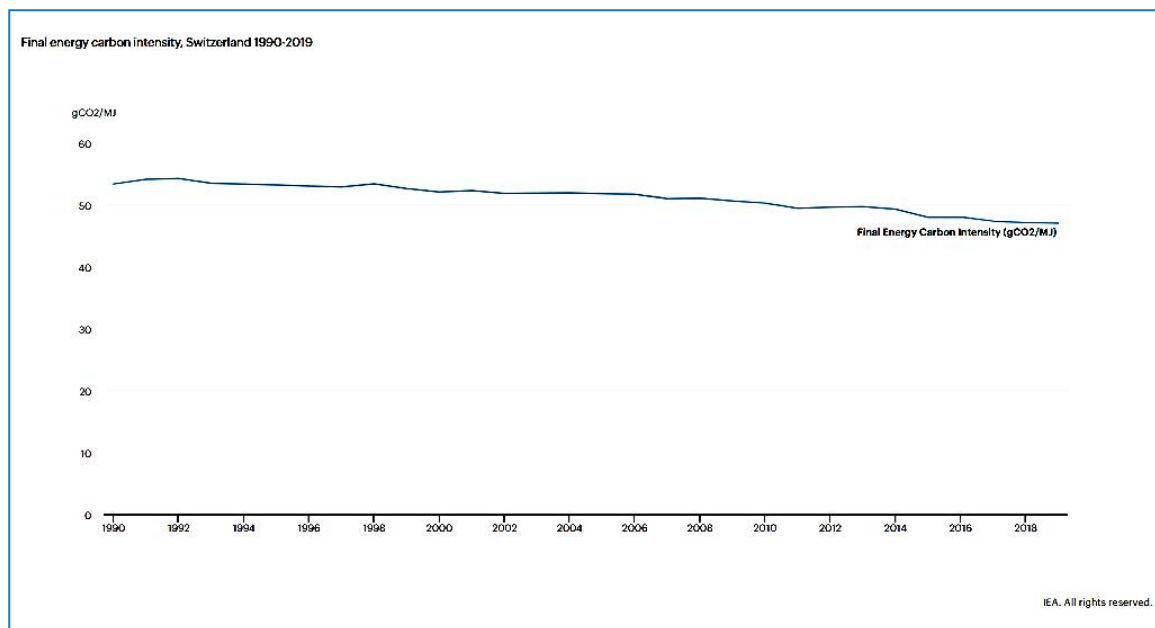
**Fig. 2.** CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)

Data from IEA, Data & Statistics

<https://www.iea.org/data-and-statistics/data-browser?country=SWITLAND&fuel=CO2%20emissions&indicator=CO2BySector>

CO<sub>2</sub> emissions in all sectors have slightly decreased but their ratio stays rather constant.

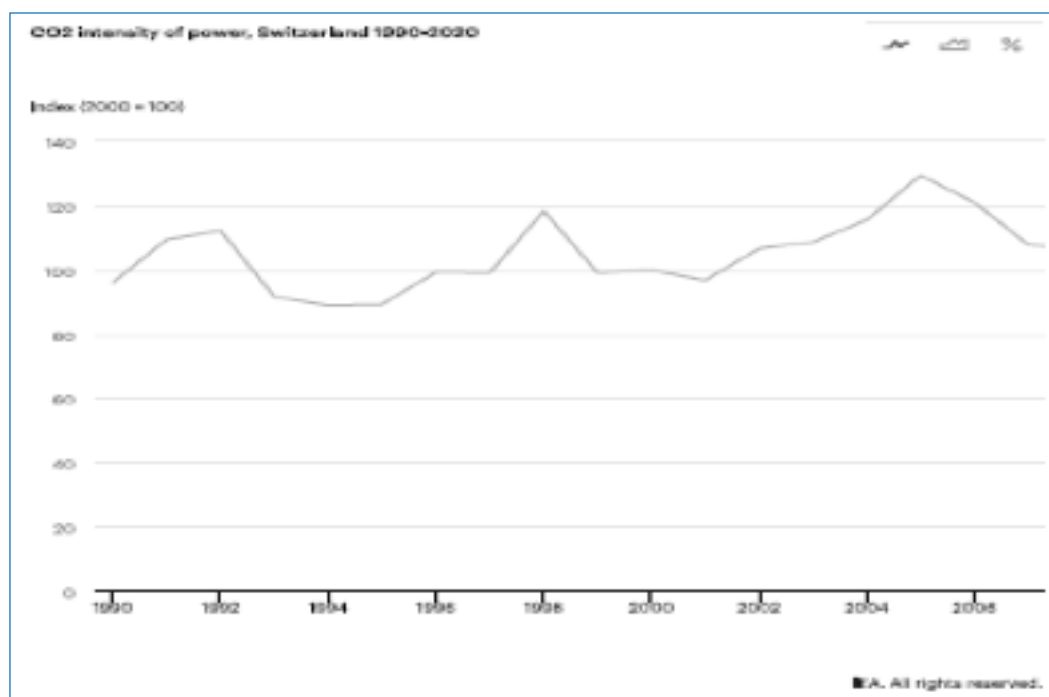
**Final energy carbon intensity: gCO<sub>2</sub>/MJ and gCO<sub>2</sub>/kWh**  
**(1 Megajoule = 0.27778 Kilowatt hours)**



**Fig. 5.** Final energy carbon intensity

<https://www.iea.org/data-and-statistics/data-browser?country=SWITLAND&fuel=CO2%20emissions&indicator=FECI>

Final energy carbon intensity decreased from 15.2 gCO<sub>2</sub>/kWh in 1990 to 13.4 gCO<sub>2</sub>/kWh in 2019.

**Electricity Carbon intensity: gCO<sub>2</sub>/kWh**

*Fig. 4.* Electricity carbon intensity (gCO<sub>2</sub>/kWh)

Switzerland has one of the lowest electricity carbon intensity among IEA countries, owing to a carbon-free electricity sector dominated by nuclear and hydro generation. However, following a 2017 referendum where the Swiss voted to gradually phase-out nuclear power, Switzerland's energy sector has thus to undergo a considerable transition.

## 2. Energy perspectives 2030 - 2050

In Switzerland, the goal is net zero emissions by 2050.

The Swiss Energy Strategy 2050 aims at maintaining the high supply standard and at the same time contributes to reducing Switzerland's energy-related environmental impact. Based on the strategy, a new Federal Energy Act entered into force on 1 January 2018. The main strategic objectives of the energy strategy are:

- measures to increase energy efficiency in buildings, mobility, industry and appliances;
- measures to increase the use of renewable energy by promotion and improved legal framework;
- withdrawal from nuclear energy (required by a popular vote in 2017). No new licenses will be given and there will be a step-by-step withdrawal – with safety being as sole criterion.

The energy strategy is based on the Energy Perspectives to 2050<sup>1</sup>. For these perspectives, various scenarios were modelled and analysed with respect to energy sources and electricity production, final energy consumption by sector, greenhouse gas emissions, etc..

<sup>1</sup> <https://www.bfe.admin.ch/bfe/en/home/policy/energy-perspectives-2050-plus.html>

## Does your country have national roadmaps regarding energy production and GHG emissions? What legal status do these documents have? What is their timeline?

Switzerland has a long-term climate strategy to 2050<sup>2</sup> to fulfil the terms of the Paris Agreement and to aim for the net zero emissions target for 2050.

Switzerland has a roadmap for electricity production and GHG reduction. In 2017, the country decided to discontinue nuclear power production and ban the construction of new nuclear plants. However, there is a discussion to prolong the use of existing nuclear plants beyond 2030 as originally decided. Part of the strategy is to import power for a time span, 2020 to 2045, until enough renewable energy is available. The amount of fossil electricity generation is already negligible today.

One pillar of the energy strategy is to improve energy efficiency per capita and raise the percentage of renewable energy.

Key indicative energy efficiency and renewable targets of the ES 2050		
Energy efficiency (indicative/non-binding targets)	Per capita energy consumption	-16% by 2020 vs. 2000 level -43% by 2035 vs. 2000 level -54% by 2050 vs. 2000 level
	Per capita electricity consumption	-3% by 2020 vs. 2000 level -13% by 2035 vs. 2000 level -18% by 2050 vs. 2000 level
	Average yearly production of renewable electricity excluding large hydro	By 2020: 4 400 gigawatt hour (GWh) By 2035: 11 400 GWh By 2050: 24 200 GWh
Renewable electricity (indicative/non-binding targets)	Average yearly production of large hydropower	By 2035: 37 400 GWh By 2050: 38 600 GWh
Source: Swiss Federal Office for Energy.		

Table 4. Key indicative efficiency and renewable targets of the ES 2050

## Roadmap for the energy mix

Switzerland projects and plans a reduction in Total Final Consumption (TFC) of more than 50% by 2050.

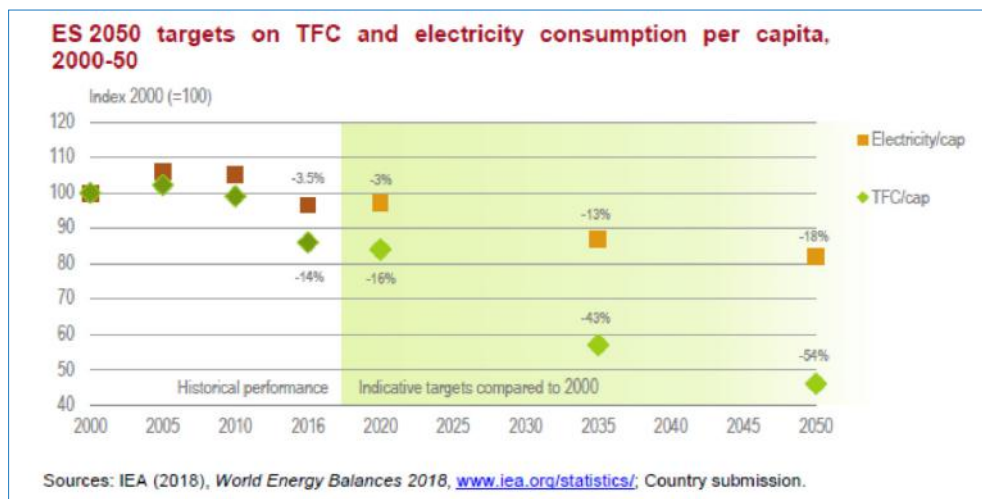


Fig. 5. ES 2050 targets on TFC and electricity consumption per capita 2000-2050

<sup>2</sup> <https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/emission-reduction/reduction-targets/2050-target/climate-strategy-2050.html>

## Roadmap for the GHG emissions (country, per capita)

Sectoral emissions reductions, 1990 and to 2020 and 2030				
Sectoral emissions (MtCO <sub>2</sub> -eq)	1990	2020	2030 (business as usual)	2030 (additional policies)
Buildings	17.1	12.0	10.6	6.9
Industry	13.0	10.7	10.4	8.7
Transport	14.9	15.7	14.9	13.6
Agriculture	7.3	6.5	6.5	5.7
Others	1.4	2.2	1.6	1.4
Total	53.7	47.1	44.0	36.3
Total (%)	100	87.7	81.8	69.5

Source: Information provided by the Swiss Federal Office for Energy.

**Table 5.** Roadmap for GHG emissions (country and par capita)  
[Energy Policies of IEA Countries: Switzerland 2018 Review – Analysis - IEA](#)

The measures of the existing CO<sub>2</sub>-law from 2000 are not sufficient to reach the targets of the climate strategy but a revised CO<sub>2</sub>-law (to encourage additional policies) was rejected in a national vote on June 13, 2021. Other options to build a legal basis for the net-zero target are currently being discussed in the Swiss parliament.

## Roadmap for the electricity mix

TWh		Realised 2019	2030 Scenario	2050 Scenario
Nuclear		25.3	8.8	0.0
Fossil	Coal	0.0	0.0	0.0
	Fuels/gas	1.9	1.6	1.0
Renewable	Hydro	40.6	41.7	44.7
	PV / wind / other renewable	4.2	10.9	39.1
Total		72.0	63.0*	84.8

**Table 6.** Roadmap for the electricity mix  
**Source:** Energieperspektiven 2050+ (admin.ch)  
 \*The missing 7.5 TWh of electricity are planned to be imported.

## CO<sub>2</sub> emissions from electricity production

The present Swiss electricity sector is highly decarbonised with 28 MtCO<sub>2</sub> equivalent in 2019.

## Energy balance (energy sources to end-uses)

The overall energy balance of Switzerland can be illustrated as shown in the graphic below. Major flows are fossil fuel imports, mainly used in transport, and electricity (generated from hydro and nuclear and other sources), mostly used in households, industry and services.

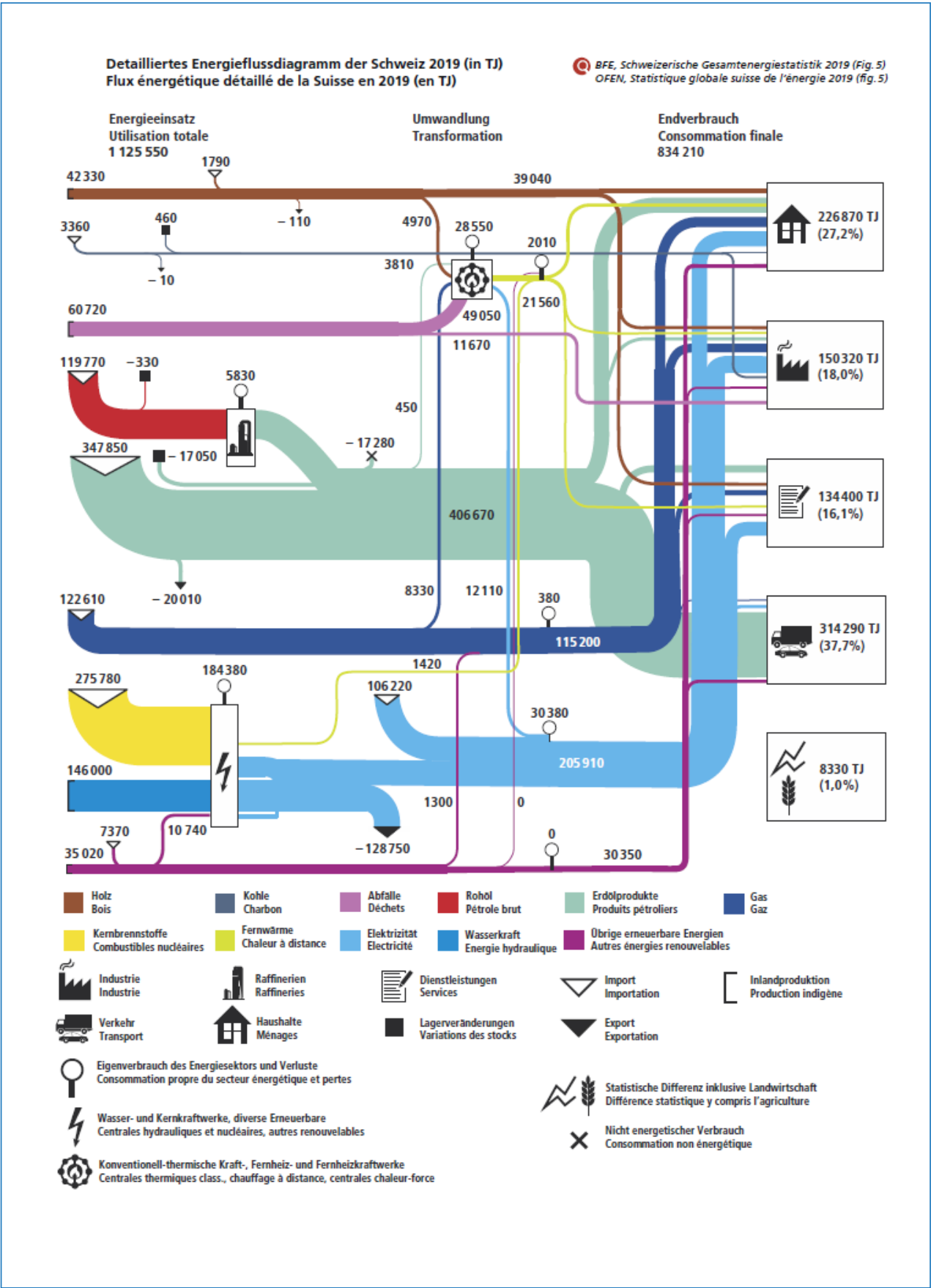


Fig. 6. Sankey diagram: Energy flow in Switzerland (all in German)

### 3. Building sector

#### 3.1. Existing buildings

##### Energy balance 2019 (energy sources to end-uses)

According to the SFOE, the Swiss buildings stock consumes approximately 100 TWh, i.e. 45% of the total end energy demand in Switzerland. Buildings also account for about one third of Switzerland's CO<sub>2</sub> emissions<sup>3</sup>. 75% of the energy consumption are used for heating purposes, 50% being based on oil and 25% on gas.

The Swiss data are based on a report from 2014.

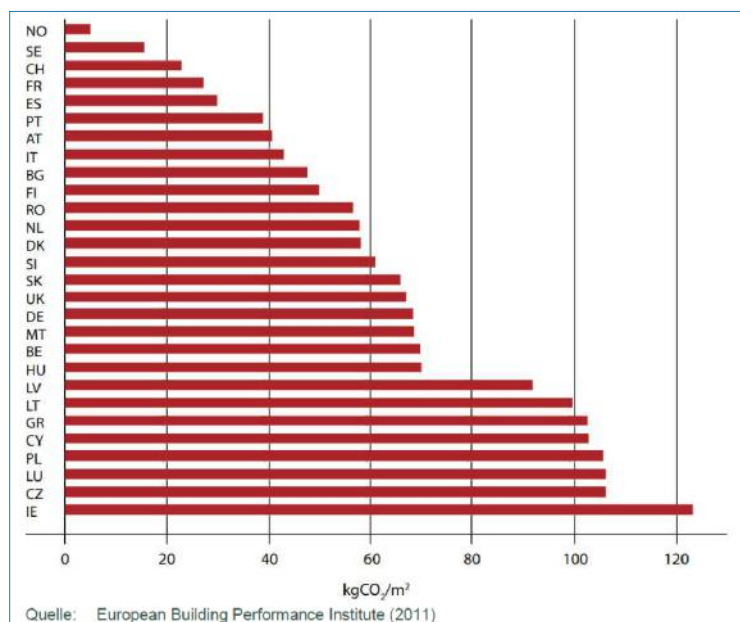
##### Energy partition between single houses, apartments buildings and office buildings

Type of building	number / Million	Million m <sup>2</sup> inhabited
All	1.8	800
Apartment buildings	0.5	350
single family homes	1.0	160
offices		60
business		40
industry		80

*Table 7.* Energy partition: single houses, apartment buildings, office buildings  
Source: [Buildings \(admin.ch\)](#)

There is no statistics for all Switzerland. The data above are estimates.

The building sector consumes about 50% of the energy demand in Switzerland. The goal is to reduce this consumption by 50% by 2050. An international comparison is shown below.



*Fig. 7.* CO<sub>2</sub> emissions per m<sup>2</sup> and by country

CO<sub>2</sub> emissions from residential buildings and commercial and public services (% of total fuel combustion) - Switzerland | Data (worldbank.org)

<sup>3</sup> See <https://www.bfe.admin.ch/bfe/en/home/efficiency/buildings.html>.

## Which systems are mostly used for heating?

- Local systems (Furnaces, electric heating, heat pumps, solar thermal panels, geothermal systems, etc.)?

The mix depends on the year of construction, for modern houses, heat pumps are the most frequent sources of heat.

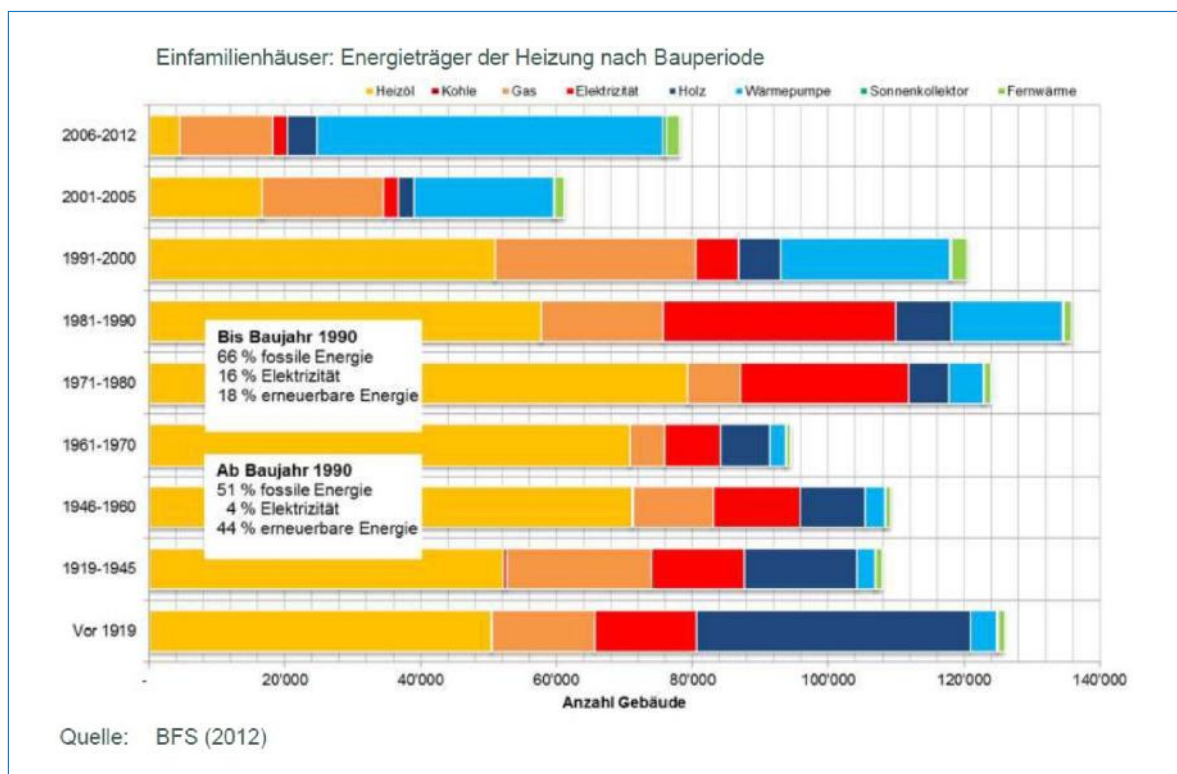


Fig. 8. One-family houses: energy type for space heating by construction period (in German)

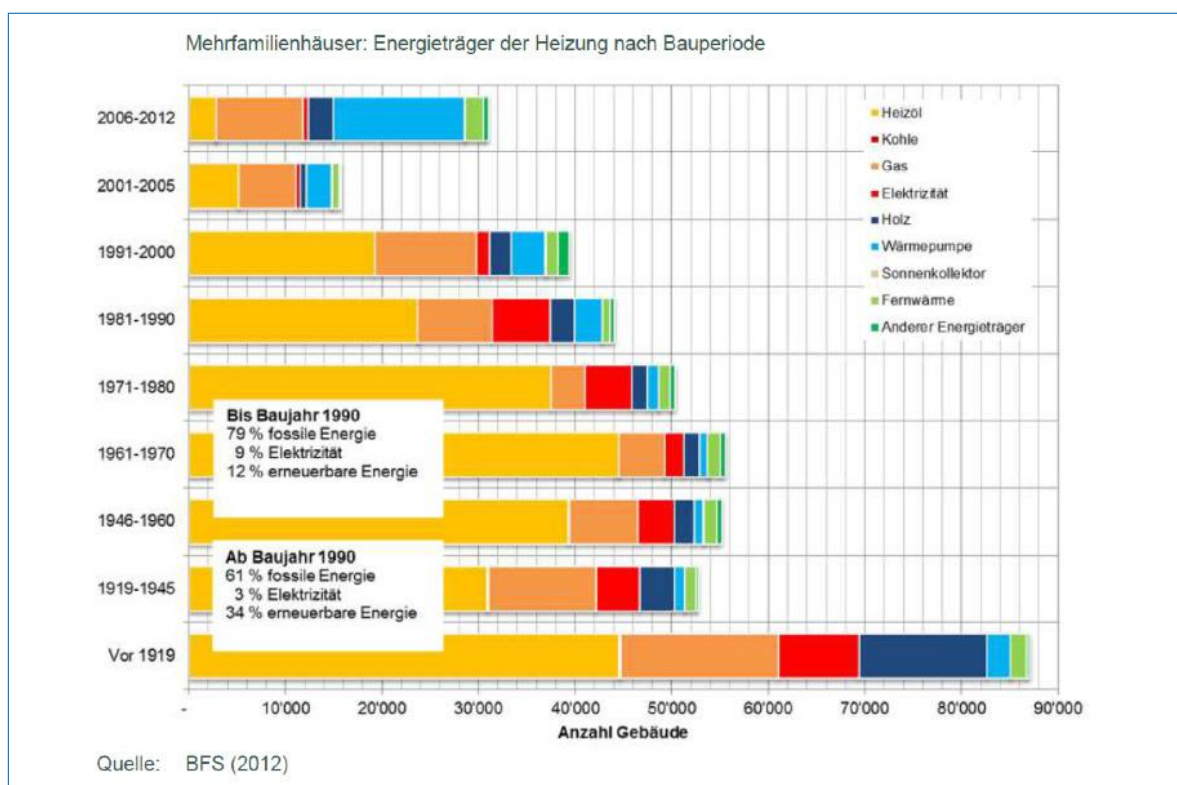


Fig. 9. Buildings for several families: energy type for space heating by construction period (in German)

- Heat networks (hot water, steam). In this case, which energy sources are used? What is the CO<sub>2</sub> content per MWh th?

Local systems are dominant, but about 1 000 thermal networks exist in Switzerland, mostly in urban areas. They supply 6 TWh to 8 TWh heat per year (according to different sources).

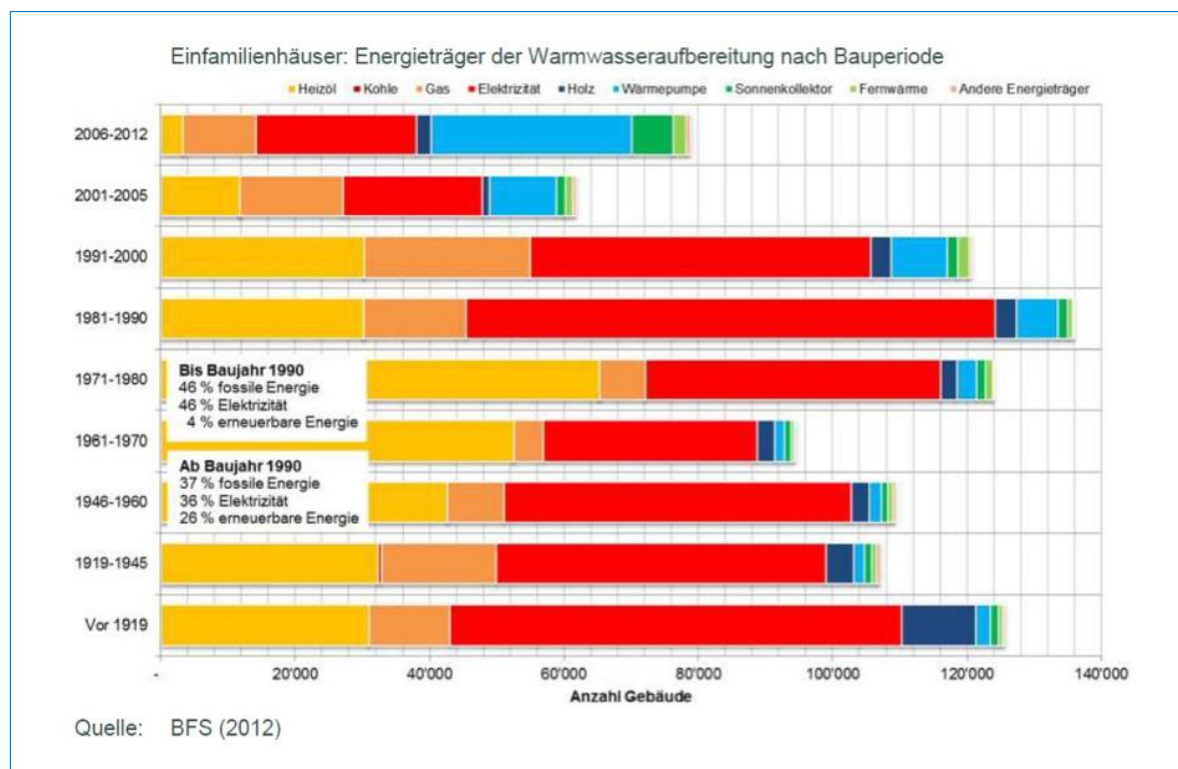


Fig. 10. One-family houses: energy type for hot water by construction period (in German)

### What are the main choices of the national policy – if there is one – to reduce the emissions from the existing stock of buildings? To make this reduction affordable?

The national energy strategy contains measures for increasing energy efficiency in buildings. These consist of a building programme that subsidises both the costs of the energy-saving renovation of buildings and the tax incentives for building renovation. The building programme supports insulation, the replacement of heating systems, as well as energy-efficient new buildings to replace older ones. The national strategy is implemented by the cantons, each of which has its own programme<sup>4</sup>.

- From a technological point of view? (Insulation, heat pumps, low CO<sub>2</sub> district network, geothermal systems, local PV production, etc.).

All of this except deep geothermal, which has not been successful in Switzerland, generating concerns around earthquakes. Depending on the region, low-depth geothermal (around 150 m ) is widespread, though.

- From a regulatory point of view? Through land ownership regulations?

Building policies are not national but cantonal. Each canton has different programmes to renew the building sector and also restrictions on new buildings. Several cantons have banned fossil fuel heating systems in new houses or even do not allow to renew existing furnaces. Other cantons require certain percentages of renewable energy for all public buildings.

<sup>4</sup> [Schweizerische Energie-Stiftung - Schweizerische Energie-Stiftung \(energiestiftung.ch\)](http://www.schweizerische-energie-stiftung.ch)  
[Gebäude - Schweizerische Energie-Stiftung \(energiestiftung.ch\)](http://www.schweizerische-energie-stiftung.ch)  
[So wird jedes Gebäude fit für mehr Energieeffizienz \(energieschweiz.ch\)](http://www.schweizerische-energie-stiftung.ch)  
[Energie sparen und Fördergelder erhalten | Das Gebäudeprogramm \(dasgebaudeprogramm.ch\)](http://www.schweizerische-energie-stiftung.ch)

- Through subsidies, different financial mechanisms? Which are the priorities: reducing CO<sub>2</sub> or energy; Better inclusivity.

Subsidies in the form of rebates or tax credits are the most common financial incentives. Direct subsidies are sometimes given to change the heating system or install PV.

The focus is on the reduction of CO<sub>2</sub>.

[Energie sparen und Fördergelder erhalten | Das Gebäudeprogramm \(dasgebaeudeprogramm.ch\)](https://www.dasgebaeudeprogramm.ch/)

- Replacing parts of the existing stock of buildings?

---

- Is there a specific roadmap for this subject?

Most cities have set up sustainability strategies and / or targets to reach net-zero in their own responsibility. The national Sustainable Development Strategy 2030<sup>5</sup> is the general framework.

### Are there some case studies or best practices you would like to share?

There are numerous interesting projects related to sustainability and energy – e.g. the winners of the Watt d'Or awards<sup>6</sup>.

## 3.2. New buildings

### Does your country have a national policy regarding new buildings?

#### If yes, what are the priorities? (For housing and for office buildings)

The federal government only plays a subsidiary role in the regulation of energy use in buildings. The Federal Constitution stipulates that the cantons have prime responsibility for implementing measures to regulate energy consumption in buildings. Therefore, this question cannot be answered in a general manner – various implementations exist among regions and cities.

Switzerland has a rather ambitious building code for new buildings and renovations.

Requirements for the building heat insulation are provided below in comparison to other countries.

	UK <sup>(3)</sup>	RO	DE	SK	CH <sup>(2)</sup>	DK	CZ	AT	PL	LT	EE	SE <sup>(4)</sup>	NO	FI
HDD	3 115	3 129	3 239	3 453	3 482	3 503	3 571	3 573	3 616	4 094	4 444	5 444	5 646	5 850
Roof	0.2	0.2	0.24	0.19	0.17 or 0.2	0.2	0.24	0.2	0.25	0.16	0.15-0.2		0.18	0.09
Walls	0.3	0.56	0.24	0.32	0.17 or 0.2	0.3	0.3	0.35	0.3	0.2	0.2-0.25		0.22	0.17
Floor	0.25	0.35	0.3		0.17 or 0.2	0.2	0.45	0.4	0.45	0.25	0.15-0.2	0.4-0.6	0.18	0.16
Window/Door	2	1.3		1.7	1.3	1.8	1.7	1.4	1.7	1.6	0.7-1.4		1.6	1.0

Quelle: Buildings Performance Institute Europe (2011)

**Table 8.** Requirements for heat insulation for new buildings – comparison between Switzerland and other European countries  
(HDD = Number of heating degree days in the year)

### Are some technologies prioritised? At the building level? At the infrastructure level? (developing district networks, prohibiting connection to the gas network...)

Not on a federal level. However, on a cantonal level, oil and gas heating are to be phased out or banned in certain areas. District heat networks are promoted, and so are heat pumps.

<sup>5</sup> <https://www.are.admin.ch/are/en/home/sustainable-development/strategy/sds.html>

<sup>6</sup> <https://www.bfe.admin.ch/bfe/en/home/swiss-federal-office-of-energy/watt-d-or/winners-of-the-watt-d-or-awards/winners-of-the-2021-watt-d-or-awards.html>

## How are they supported? Through regulations? Subsidies?

Both, depending on the area. Mainly subsidies, though.

## Are there some case studies or best practices you would like to share?

- Steel industry (including mining): basically not existing in Switzerland
- Cement industry: we will comment
- Oil industry (refinery): basically not existing in Switzerland
- Chemical industry (in particular petrochemicals: ammonia, ethylene, plastic...): only fine chemical industry in Switzerland.
- Information and telecommunication
- Food and agriculture (from farm to fork)

## 4. Industry and Agriculture

### 4.1. Cement industry

Data are based on the website of CEMSuisse<sup>7</sup>, not on government data.

**What is the energy balance (energy sources used)?**  
**And the GHG intensity, compared to other countries?**

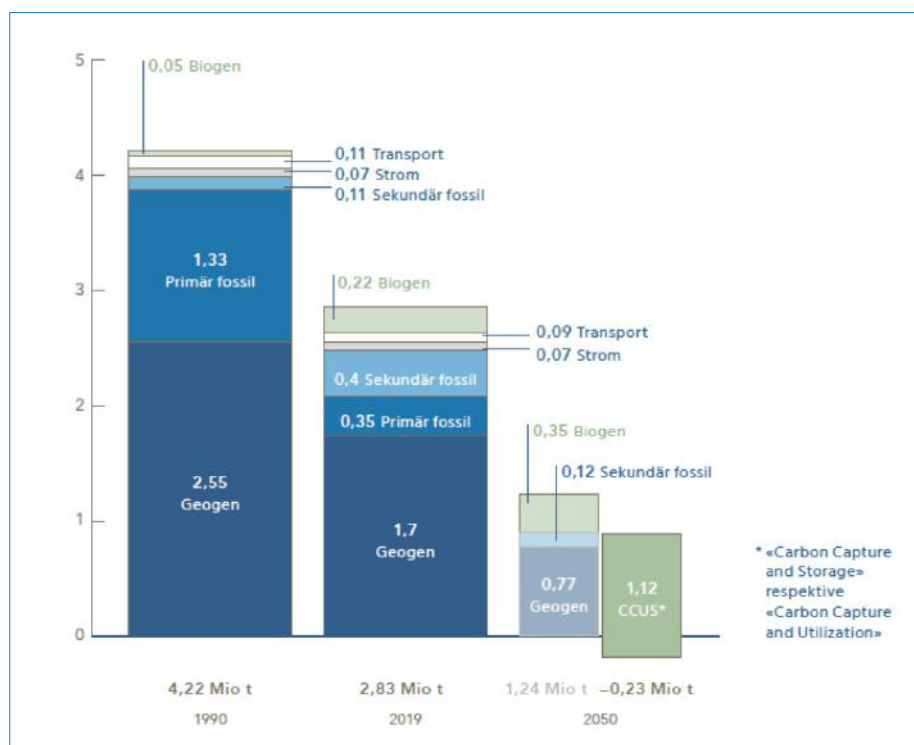


Fig. 11. Evolution of energy sources for cement production 1990, 2019, 2050 (in German)

<sup>7</sup> [Verband der Schweizerischen Cementindustrie - cemsuisse](http://www.cemsuisse.ch)

## Are the best available low carbon technologies used/considered?

If not, is it an economic problem? A matter of regulation? Or some social issues?

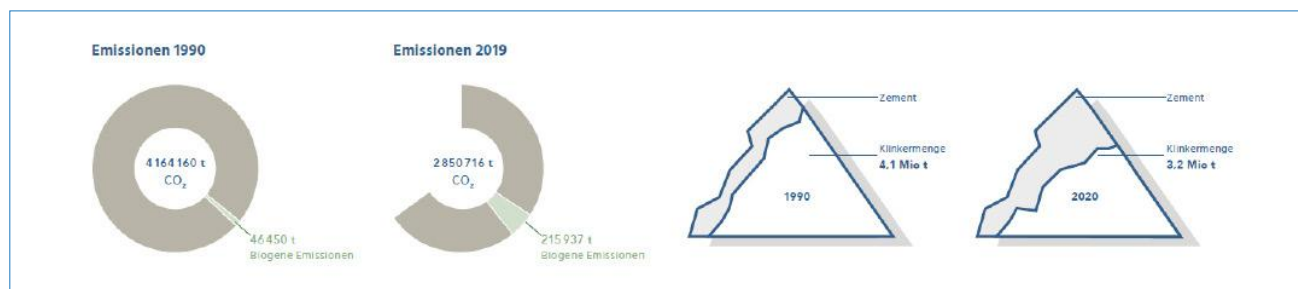


Fig. 12. Evolution of CO<sub>2</sub> emissions 1990 – 2019 and Cement/Clinker share 1990, 2020

Low carbon technologies are considered. The greatest reduction has been achieved by using lower carbon emission cement types<sup>8</sup>.

The other approach is to use new building architecture with less cement and radically new supporting structures<sup>9</sup>.

EMPA, the Swiss federal material research institute runs a large prototype building (NEST) to investigate low carbon building<sup>10</sup>.

## Is there a roadmap to decrease GHG emissions for 2030 - 2050

If yes, what are the intermediary steps?

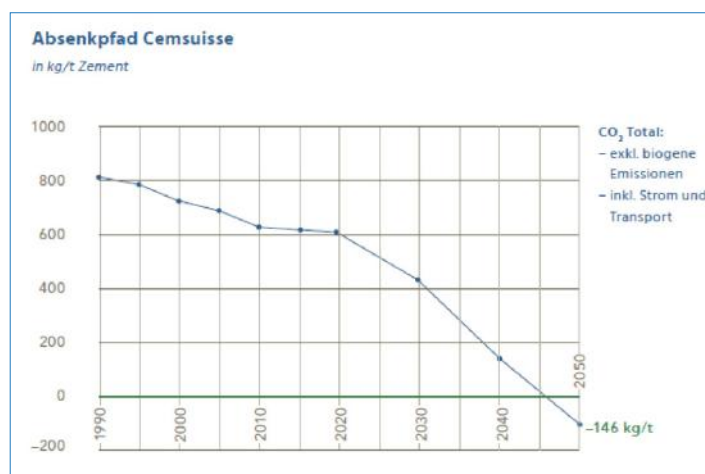


Fig. 13. Evolution of CO<sub>2</sub> emissions from cement manufacturing 1990 – 2050

Is the implementation of low-carbon technologies helped by the government? For refurbishing or replacing equipment? How are public authorities pushing the transformation? Through benchmarking? Audits?

Since 2008, Switzerland has a CO<sub>2</sub> levy<sup>11</sup>, which has increased from 12 CHF/tonne in 2008 to nearly CHF 100 now. Operators of greenhouse gas-intensive installations can be exempted from the CO<sub>2</sub> levy if they commit to reducing their emissions. Industries with high energy consumption have consistently invested in CO<sub>2</sub> reduction. There are no direct or other subsidies.

<sup>8</sup> See Holcim's Climate responsibility: <https://holcim.com/sustainability/net-zero>

<sup>9</sup> Center for Augmented Computational Design in Architecture, Engineering and Construction | ETH Zurich: <https://designplusplus.ethz.ch/>

<sup>10</sup> Empa - NEST - STEP2

<sup>11</sup> <https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/reduction-measures/co2-levy.html>



## 4.2. Chemical Industry

### What is the energy balance (energy sources used)? And the GHG intensity, compared to other countries?

Scienceindustries<sup>13</sup>, the association of the Swiss Chemical, Pharma and Life Science industries, states the following mix for the energy consumption of their member industries (data from 2019):

- 35% natural gas
- 33% electricity
- 20% waste processing (fossil sources)
- 7% renewable energies (incl. biogenic wastes)
- 4% other fossil fuels
- 1.4% fuel oil
- 0.7% district heating
- 0.4% unspecified

We are not aware of a specific study on the energy source mix of electricity used in the Swiss chemical industry. Therefore, we assume the average Swiss mix stated below. However, the electricity market in Switzerland is liberalised for large consumers (over 100 000 kWh annual consumption) and these consumers (including part of the chemical industry) might purchase electricity with a different source mix.

Source mix for electricity consumed in Switzerland 2019:

- 75% renewable, mostly (66%) hydropower
- 21% non-renewable, mostly (21%) nuclear energy
- 4% not specified sources, 'grey energy'

The monitoring reports on the Swiss energy strategy<sup>14</sup> state that the CO<sub>2</sub> emissions of the entire industry have been slightly decreasing since 2000; however, we cannot comment on how this compares to other countries and for the chemical industry in particular. It is a minor part of industrial emissions.

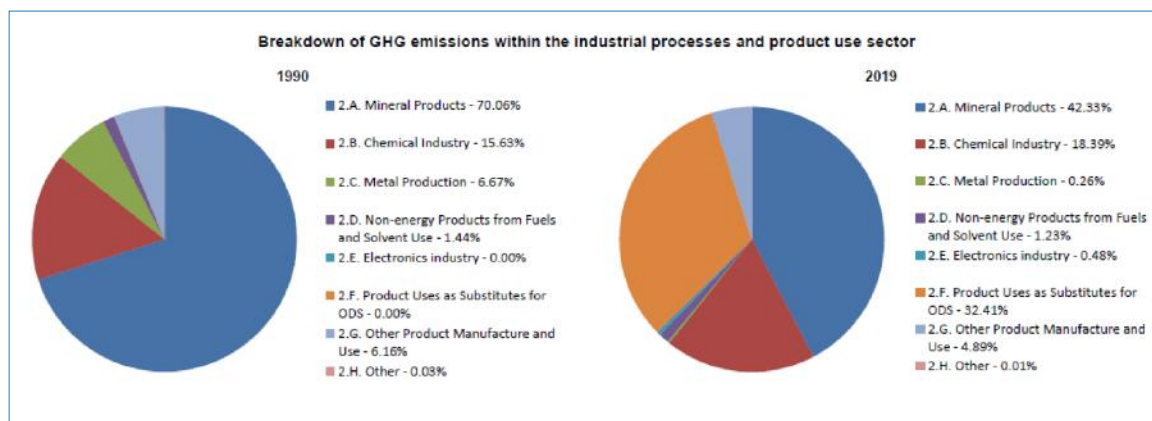


Fig. 15. Breakdown of GHG emissions from industrial processes and product use, 1990 and 2019  
[Switzerland - Countries & Regions - IEA](https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/monitoring-energy-strategy-2050.html)

Switzerland has the lowest carbon intensity among IEA countries, owing to a carbon-free electricity sector dominated by nuclear and hydro generation.

<sup>13</sup> <http://www.scienceindustries.ch/en/home>

<sup>14</sup> <https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/monitoring-energy-strategy-2050.html>

**Are the best available low carbon technologies used/considered?****If not, is it an economic problem? A matter of regulation? Or some social issues?**

Low carbon technologies are considered to reduce the CO<sub>2</sub> levy mentioned above<sup>15</sup>. A major driver would be importing low carbon feedstocks, and building the chemical industry on renewable carbon sources. However, this is only possible in a European context (see in the German Chemical Industry the renewable Carbon Initiative<sup>16</sup>).

The chemical industry in Switzerland is not engaged in the production of primary chemicals but rather imports plastics and the required chemicals *e.g.* for synthesis of fine and specialty chemicals. According to data published by the Swiss customs, in 2019 the net-import (*i.e.* the import minus the export) of chemicals and plastics amounted to 1.6 Mt. Based on the carbon content of the products, we estimated that this corresponds approximately to 1.5 Mt (65 PJ) of oil (see Supplementary Information for details). Furthermore, the Swiss energy statistic reported the consumption of 0.4 Mt of oil (17 PJ) for non-energetic purposes, for example as lubricants for machines and vehicles or as bitumen for road construction. Overall, the non-energetic use of oil in Switzerland amounts to 1.9 Mt, which corresponds to 20% of the total energetic oil consumption (9.5 Mt, 407 PJ) and to 9% of the total final energy demand (Fig. 1c).

Taken from doi:9.2533/chimia.2021.788

**Is there a roadmap to decrease GHG emissions for 2030 - 2050****If yes, what are the intermediary steps?**

Scienceindustries states in a position paper its support to the Swiss strategy to reach net zero in 2050. Four fields of measures are prioritised:

- The application of innovative technologies
- Target agreements with the authorities that are linked to reductions in CO<sub>2</sub> taxes
- Compensation of greenhouse gas emissions
- Emission trading

**Is the implementation of low-carbon technologies helped by the government?****For refurbishing or replacing equipment? How are public authorities pushing the transformation? Through benchmarking? Audits?**

See *Section 4.2* (CO<sub>2</sub> levy). In addition, very strict regulations on the emission of Volatile Organic Compounds (VOC) are enforced, requiring the chemical industry to mainly work with aqueous and not solvent systems.

**Are there incentives for carbon capture, utilisation, and storage? How?**

There are now official guidelines on how to reduce CO<sub>2</sub> emission.

<sup>15</sup> [CO<sub>2</sub> levy : admin.ch](https://www.admin.ch/co2levy)

<sup>16</sup> [www.renewable-carbon-initiative.com](https://www.renewable-carbon-initiative.com)

**If relevant, what about recycling? What percentage is recycled? What are the obstacles to increase recycling? Is a policy to increase recycling already in place or in project?**

Every year, around 1 million tonnes of plastics are used in Switzerland – this corresponds to 125 kg per capita (reference year 2010). Around 250 000 tonnes are made into durable products (e.g. plastic window frames) and remain in use for a fairly long period. Every year, around 780 000 tonnes of plastic waste is generated, more than 80% of which (around 650 000 tonnes) is used for energy recovery in incinerators and over 6% in cement factories. About 80 000 tonnes are recycled.

See [Plastics \(admin.ch\)](#).

**Are there some case studies or best practices you would like to share?**

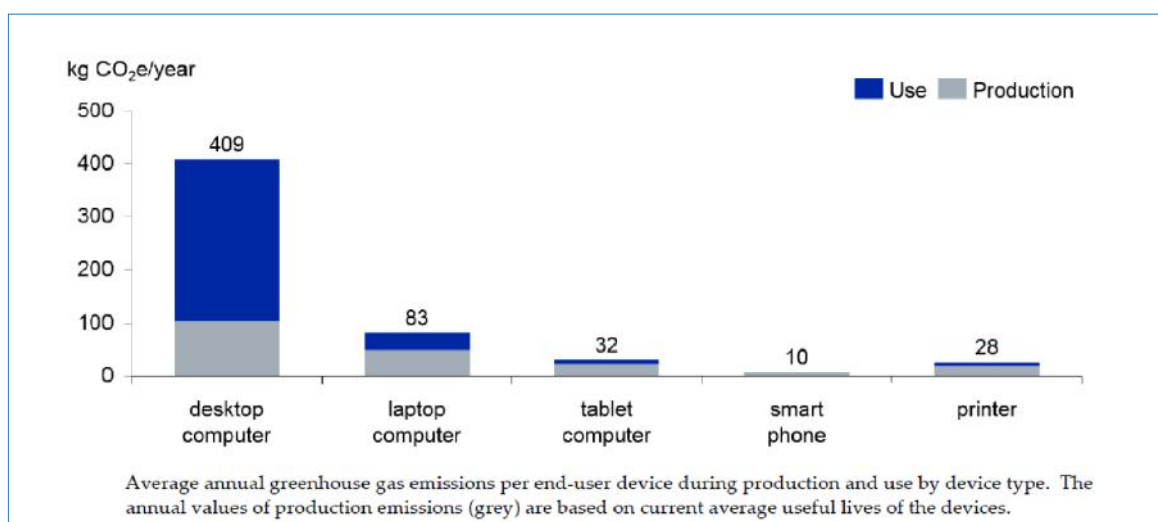
Nothing in particular

**4.3. ICT**

[Microsoft Word - 2017\\_Study\\_Digitalization\\_Climate\\_Protection\\_KORRIGIERT.docx \(wwf.ch\)](#)

**What is the energy balance (energy sources used)?  
And the GHG intensity, compared to other countries?**

The Swiss electricity mix is used.



*Fig. 16.* CO<sub>2</sub> emissions from the consumption of electricity for the use and production of IT devices

**Are the best available low carbon technologies used / considered?  
If not, is it an economic problem? A matter of regulation? Or some social issues?**

---

## Is there a roadmap to decrease GHG emissions for 2030 - 2050

### If yes, what are the intermediary steps?

No, the ICT sector is expected to grow.

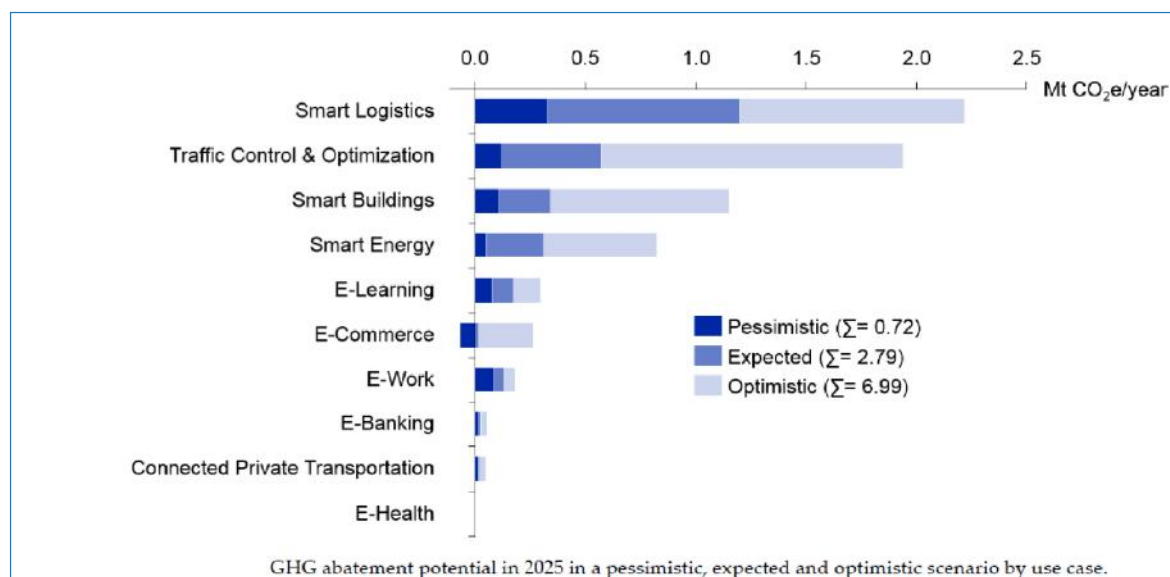


Fig. 17. Abatement potential for GHG emissions in 2025: Pessimistic, expected, and optimistic scenarios by use case

## 4.4. Agriculture

### What is the energy balance (energy sources used)?

### And the GHG intensity, compared to other countries?

From [CHE\\_ghg\\_profile.pdf \(unfccc.int\)](https://di.unfccc.int/ghg_profiles/annexOne/CHE/CHE_ghg_profile.pdf)<sup>17</sup>

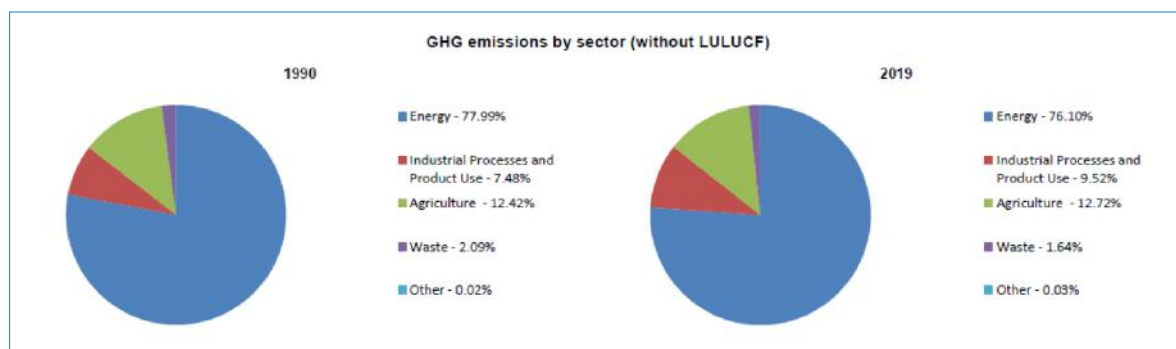


Fig. 18. GHG emissions by sector (without LULUCF), 1990 and 2019

[Swiss Agricultural Greenhouse Gas Inventory \(admin.ch\)](https://di.unfccc.int/ghg_profiles/annexOne/CHE/CHE_ghg_profile.pdf)

[Microsoft Word - Klimastrategie Landwirtschaft d \(admin.ch\)](https://di.unfccc.int/ghg_profiles/annexOne/CHE/CHE_ghg_profile.pdf)

<sup>17</sup> [https://di.unfccc.int/ghg\\_profiles/annexOne/CHE/CHE\\_ghg\\_profile.pdf](https://di.unfccc.int/ghg_profiles/annexOne/CHE/CHE_ghg_profile.pdf)

Is there a roadmap to decrease GHG emissions for 2030 - 2050

If yes, what are the intermediary steps?

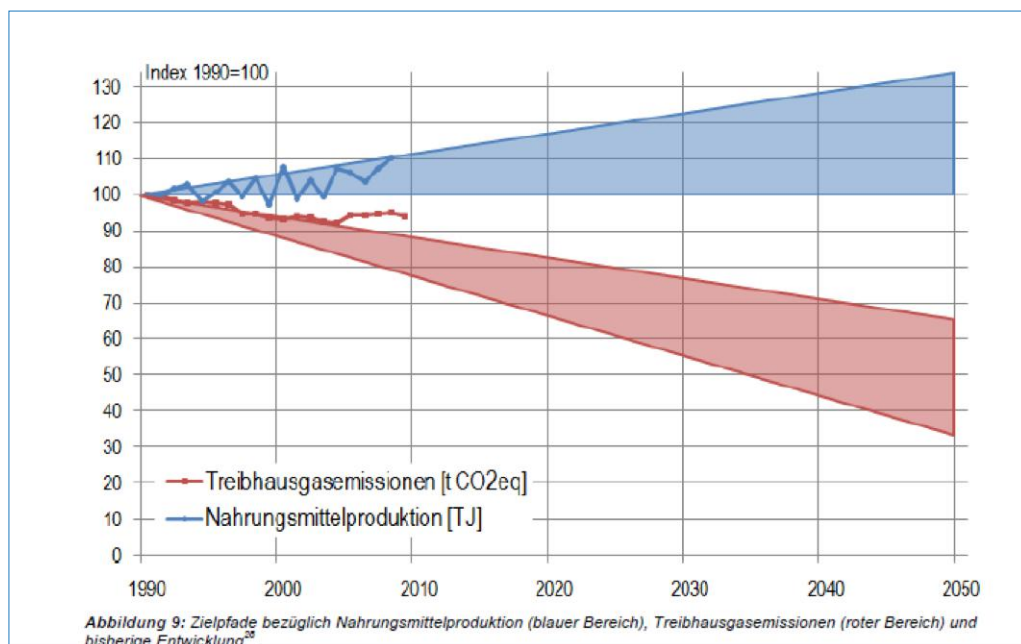


Fig. 19. Target pathways for GHG emissions (tCO<sub>2</sub>e) and energy use in food production (TJ)

There is a road map but not many important measures to ensure it will be implemented.

**Are there incentives for carbon capture, utilisation, and storage? How?**

The GHG reduction plans for agriculture are not very well implemented.

Table of Contents

Introcuction ..... 424

1. National Energy Profile ..... 424

2. Energy Perspective 2030 - 2050 ..... 426

3. Buildings ..... 429

3.1. Existing Buildings ..... 429

3.2. New Buildings ..... 430

4. Industry ..... 430

4.1. Chemicals ..... 430

4.2. Steel ..... 430

## Introction

1. This UK response has been drafted by the following contributors:
  - Mr Andrew Haslett – Fellow of the Royal Academy of Engineering and Fellow of the Institution of Chemical Engineers.
  - Dr Julie Godefroy – Head of Sustainability at the Chartered Institution of Building Services Engineers (CIBSE), and member of the NEPC Decarbonisation Working Group.
  - Dr Chris Melvin – Member of the Institute of Materials, Minerals and Mining.
2. The draft has also been reviewed by the National Engineering Policy Centre (NEPC) Decarbonisation Working Group, which guides the NEPC's net zero policy project. The NEPC is a partnership hosted by the Royal Academy of Engineering that represents 43 different UK engineering organisations, which in turn represent 450 000 engineers. The NEPC exists to give policymakers a route to advice from across the whole engineering profession, and to give the engineering profession a unified voice on shared challenges.
3. The industry sectors considered in part three of this response are chemicals and steel.
4. Headings in the text align with the top-level questions of the questionnaire.

## 1. National Energy Profile

For consistency with other national inputs, this section uses IEA country data. The data are shown on a territorial basis – for England, Scotland, Wales and Northern Ireland.

Key data for 2019 are:

- Population 66.8 M
- Total energy consumption 1 646 TWh
- Electricity consumption 317.3 TWh
- Total CO<sub>2</sub> emissions 342 Mt
- Energy consumption per capita 24.6 MWh
- Electricity consumption per capita 4.8 MWh
- CO<sub>2</sub> per capita 5.1 t

The UK economy has a higher share of services and a lower share of manufacturing than many other developed economies. Energy supply to transport and buildings are the major end-uses. Oil and gas products are used in chemicals production, but to a lesser extent than many other European economies.

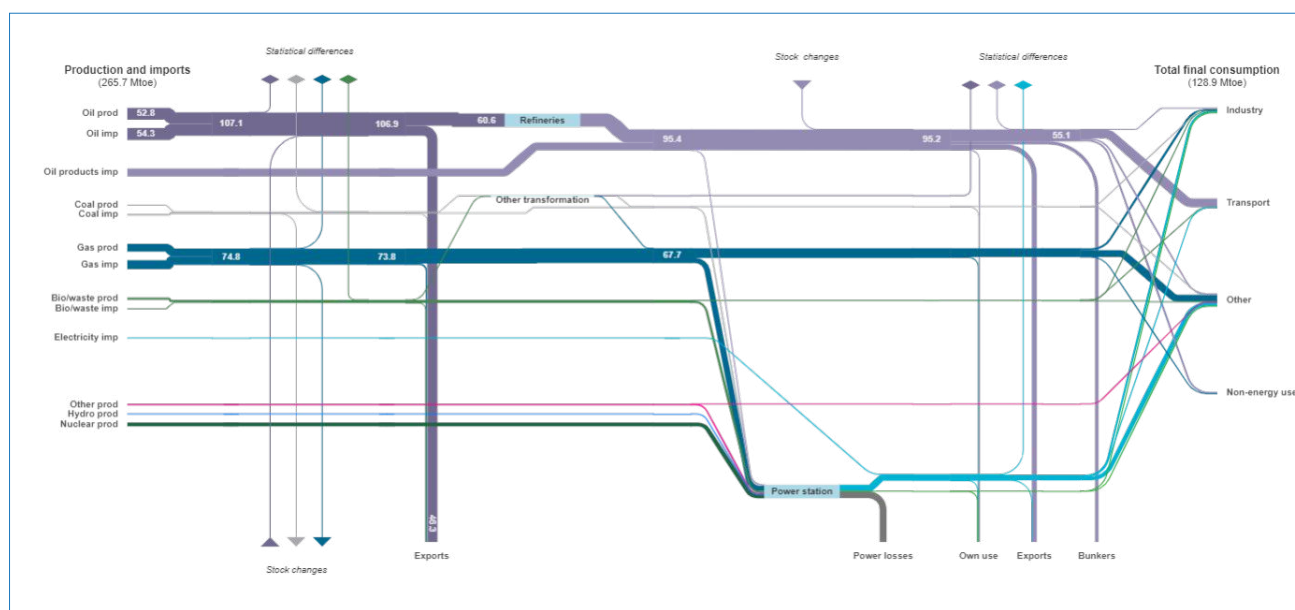


Fig. 1. IEA UK 2018 Energy Sankey Diagram

The UK is also notable in that natural gas boilers dominate in the supply of space heating and hot water supply; cooking is split between electricity and gas. Electricity and oil are the next most significant heating sources (in areas outside of the gas network). Until recently, the UK was the world's largest market for fossil fuel boilers.

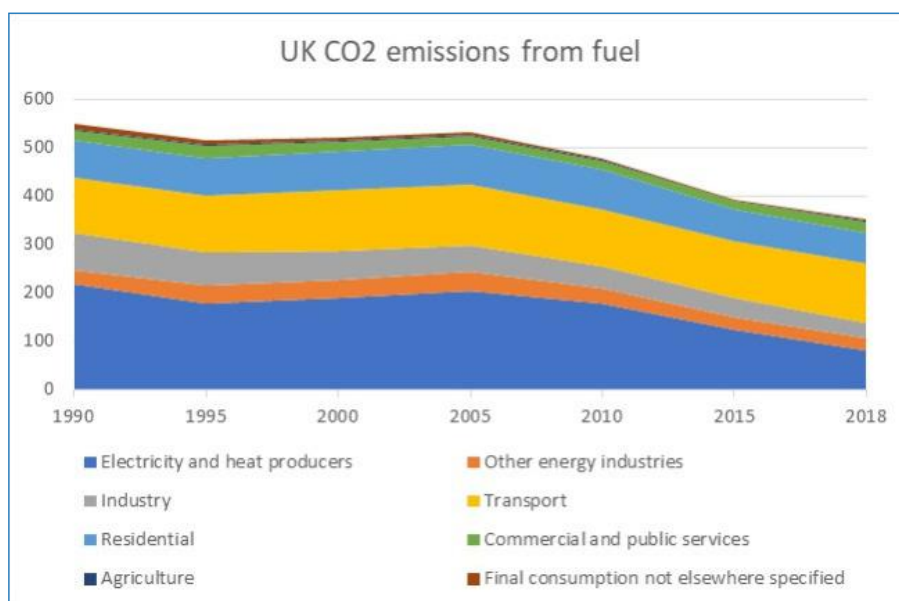


Fig. 2. UK CO<sub>2</sub> emissions from combustion by source

UK combustion emissions are consistent with this pattern of energy supply and use. Progress since 1990 has been largely in electricity generation, with efficiency gains in transport and buildings offset by increased demand. Industry has improved efficiency, but the largest gains have come from switching to less energy intense economic activities.

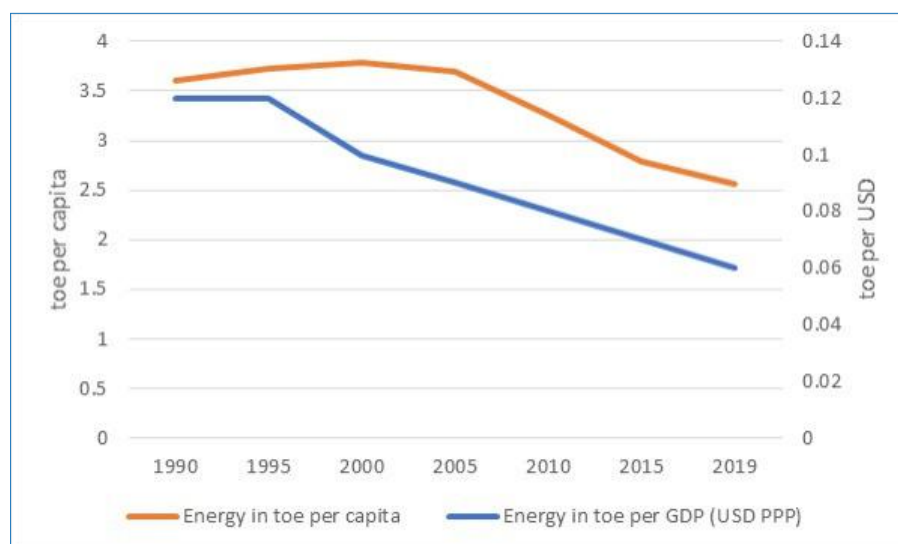


Fig. 3. Energy Int

The UK is notable for:

- A very diverse and relatively inefficient stock of residential, commercial and institutional buildings
- A short but relatively intense heating season, for which boilers are an ideal solution, but so far limited penetration of air conditioning
- Excellent offshore wind resource but a northerly location with low winter sunlight and frequent cloud cover
- Good potential for economic offshore secure geological CO<sub>2</sub> storage
- Existing brine-mined salt cavern hydrogen storage with potential for major expansion

- High average population density in combination with large areas of much lower population density and a diverse set of requirements for the movement of people and goods
- A service-oriented economy with increasing business and private use of information and communications technologies
- Potential for increased economic value from land, including afforestation and peatland rewetting
- Potential for significant health improvements through dietary changes (including switching to more plant fats and proteins and less animal fats and proteins) and through improved air quality, active travel, and more comfortable and energy efficient homes.

Primary data sources for the UK are the Digest of UK Energy Statistics<sup>1</sup> and the National Atmospheric Emissions Inventory<sup>2</sup>.

## 2. Energy Perspective 2030 - 2050

---

The existence of anthropomorphic climate change, the potential local and global damaging effects of climate change and the need to achieve Net Zero are widely understood and supported in the UK. Net Zero targets for England, Scotland and Wales were set by three different political parties from across the spectrum. Other political parties are if anything even more supportive of Net Zero. The Northern Ireland Assembly is currently consulting on its Energy Strategy.

Following the publication of an Energy Strategy in 2003 which committed the UK to significant reductions in greenhouse gas emissions, the Climate Change Act of 2008 established a target of 80% reduction compared to 1990 levels (effectively 85% for energy related emissions) and a governance mechanism in which an independent statutory body (the Climate Change Committee or CCC) proposes a series of 5-year Carbon Budgets. Once accepted by Parliament, the CCC then reports on progress against budgets and gaps in policy to deliver future budgets. The CCC has staff and resources to commission research and analysis.

Given the urgency of moving beyond electricity to the greater challenges of buildings, transport and industry, the role of the CCC in assessing and critiquing the development and deployment of policy and plans will assume greater importance. How fundamental differences between the CCC and different levels of government will be resolved, and interact with the processes of democracy and the legal system, is untested.

In June 2019, the UK became the first major economy to set a legally binding Net Zero greenhouse gas emissions target (for 2050). The Sixth Carbon Budget covers the period from 2033 to 2037 and was adopted by Parliament in April 2021. This commits the UK to reduce emissions by 78% (from 1990) by 2035, explicitly including a UK share of international aviation and shipping (IAS) emissions in the legal target for the first time. "Consumption" emissions, those of products made abroad but used in the UK, are increasingly discussed in CCC reports but not yet included in formal targets.

---

<sup>1</sup> <https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes>

<sup>2</sup> <https://naei.beis.gov.uk/overview/ghg-overview>

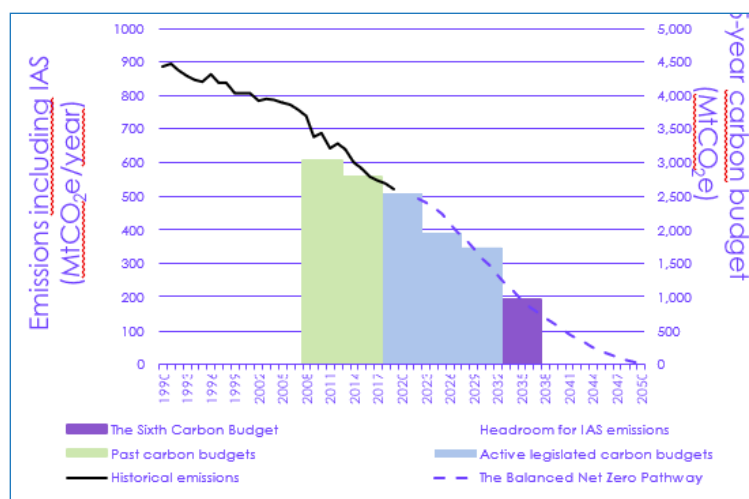


Fig. 4. UK Carbon Budgets, including projection to 2050

BEIS (2020) Provisional UK greenhouse gas emissions national statistics 2019; CCC analysis. Notes: Emissions shown including emissions from international aviation and shipping (IAS) and on an AR5 basis, including peatlands. Adjustments for IAS emissions to carbon budgets 1-3 based on historical IAS emissions data; adjustments to carbon budgets 4 and 5 based on IAS emissions under the Balanced Net Zero Pathway.

Carbon Budgets include all territorial greenhouse gas emissions (as CO<sub>2e</sub>) plus IAS. The legally binding target is total emissions over each 5-year period, but the CCC recommendation is backed by ~1,000 pages of analysis which shows how the budgets might be economically and feasibly delivered, the scientific and political context and the policy mechanisms that might be appropriate.

As the chart shows, the period 2025 to 2035 is critical in moving the pathway beyond decarbonising electricity to decarbonising transport, buildings and industry and laying the foundations for a zero-carbon economy by 2050. A major expansion of electricity supply will be required to support this, along with establishing a functioning low-carbon hydrogen economy, bio-energy with CCS and at least one Direct Air Capture plant of 1MTe per year (or more) capture rate.

Over time the CCC has established itself as the shop window for a broad community of academic and industrial interests involved in climate change analysis, planning and implementation.

The UK Energy Transition involves all aspects of social, industrial and infrastructure planning. The lead actors in this are:

- UK Parliament, Scottish Parliament, Welsh Senedd and Northern Ireland Assembly
- The CCC
- The Electricity/Energy System Operator for Great Britain (GB ESO)
- The Office of Gas & Electricity Markets (Ofgem)

For example – establishing a successful UK offshore wind industry and driving down the cost from around £140 per MWh to £70 per MWh between 2010 and 2020, involved support for ports, technology and supply chain support, electricity market mechanisms, offshore and onshore regulated assets for transmission, skills and training development etc. Many public and private sector organisations were involved in this. The CCC central scenario foresees major further technology and deployment challenges for offshore wind.

Ofgem has a number of key roles in this:

- Understanding and protecting the interests of energy customers
- Agreeing financial settlements for regulated asset base companies, principally networks
- Funding and structuring innovation support for infrastructure assets and technologies
- Setting direction for market and regulatory changes and sponsoring individual projects

The Department for Business Energy and Industrial Strategy (BEIS) is currently considering a proposal from Ofgem to strengthen and expand the role of the GB ESO to include both operations and strategic planning. The scope of this role may be as narrow as the electricity system or encompass the whole energy system, for example including heat distribution. The island of Ireland has its own integrated electricity system.

There is increasing focus on the planning responsibilities of local and regional authorities for buildings and transport and how local plans for building refurbishment, electric vehicle charging, public transport and local energy networks can be established in partnership with network companies, Ofgem and a strengthened ESO.

At a UK level, there are three key sources for energy planning:

- The CCC Carbon Budget reports<sup>3</sup> and supporting information,
- The GB ESO Future Energy Scenarios<sup>4</sup>,
- Policy documents from the UK, Scottish, Welsh and Northern Ireland governments

Examples of policy documents include the UK Prime Minister's 10-point plan<sup>5</sup>, the recent Transport strategy<sup>6</sup> and Hydrogen Strategy<sup>7</sup>, and the expected Heat & Buildings Strategy and significant updates to the Smart Energy strategies.

These strategies share certain characteristics:

- A limited portfolio of options to be developed, tested and deployed in combination as a whole system but significant uncertainty about citizen engagement (for example on diet) and on the overall energy mix, notably in terms of the size and shape of the hydrogen economy and the mix of solutions for building energy efficiency and heating
- An expectation that commercial forces will discover and deploy the best solutions within an overall framework set by government
- Short-term targets up to 2030-35 within a set of broader possibilities by 2050
- Discussion of supply chain, regulatory and planning capacity building, along with debate about citizen engagement and overall social capacity and change (see for example the first part of the CCC Policy report<sup>8</sup>)
- Greater or lesser integration into wider strategies for example for industry, housing, healthcare, skills development and employment and the social and physical infrastructure required to address regional inequalities in opportunity and outcomes

The core of UK strategy is electrification by offshore wind, supported by onshore wind, solar PV, nuclear, bioenergy with CCS, and hydrogen. In addition, there will be power balancing from natural gas with CCS and stored hydrogen. Debate is ongoing on the role of hydrogen in industry, transport and heating and competition between different production routes for low-carbon hydrogen<sup>9</sup>.

A smart energy system will be required, to manage vehicle charging and heating to match renewable energy supply and network capacity. This will require technical, market structure and behavioural changes. An expected increase in EVs on the road from 0.5M in 2021 to over 10M in 2030 means that progress with managed charging is now a priority<sup>10</sup>. The UK Smart Meter programme is an important enabler for this<sup>11</sup>.

<sup>3</sup> <https://www.theccc.org.uk/publication/sixth-carbon-budget/>

<sup>4</sup> <https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2021>

<sup>5</sup> <https://www.gov.uk/government/news/pm-outlines-his-ten-point-plan-for-a-green-industrial-revolution-for-250000-jobs>

<sup>6</sup> <https://www.gov.uk/government/publications/transport-decarbonisation-plan-7> <https://www.gov.uk/government/publications/uk-hydrogen-strategy>

<sup>7</sup> <https://www.gov.uk/government/publications/uk-hydrogen-strategy>

<sup>8</sup> <https://www.theccc.org.uk/wp-content/uploads/2020/12/Policies-for-the-Sixth-Carbon-Budget-and-Net-Zero.pdf>

<sup>9</sup> See for example - <https://www.autocar.co.uk/car-news/industry-news-government-and-legislation/government-pledges-%C2%A33m-create-uk%E2%80%99s-first-hydrogen>, <https://h21.green/projects/h21-north-of-england/>, <https://www.hy4heat.info/>, <https://www.energylivenews.com/2021/03/17/uks-first-carbon-capture-project-given-72m-funding/>, <https://www.storegga.earth/projects/> and <https://www.upstreamonline.com/energy-transition/early-engineering-starts-on-major-direct-air-capture-facility-in-uk/2-1-1030184>

<sup>10</sup> <https://www.zemo.org.uk/work-with-us/energy-infrastructure/projects/EVP20-1-EV-Energy-Taskforce.htm>

<sup>11</sup> See for example - [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/937296/future-coordinated-consumer-engagement-govt-response.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/937296/future-coordinated-consumer-engagement-govt-response.pdf)

There are two kinds of shorter-term markers:

- Specific legislative and regulatory actions - for example to ban the sale of fossil fuel vehicles by 2030, mandate low-carbon heating for new housing by 2025 and switch the electricity market to settling supplier costs based on individual half-hourly metering
- Innovation support activities by Ofgem<sup>12</sup> (regulated asset companies), Innovate UK<sup>13</sup> (industry) and the Business Department<sup>14</sup> (policy support)

### 3. Buildings

#### 3.1. Existing Buildings

Buildings have a significant part to play in reaching UK Net Zero: in 2018, energy use in buildings accounted for the following (IEA Global Status, 2019):

- 30% of global final energy use, of which 22% from residential and 8% from non-residential buildings
- 28% of energy-related\* carbon-equivalent emissions, of which 17% from residential and 11% from non-residential buildings.

Buildings are responsible for a significant part of heating energy use, with homes alone responsible for 60% of UK heat energy use. Residential buildings are acknowledged to be a significant area for policy action, due to their contribution to total emissions, relative inefficiency, and high numbers of households in fuel poverty.

UK reliance on gas for heating is one of the highest among OECD countries, at around 80%. A large majority of homes (around 85%) are heated with gas boilers. The non-domestic sector is also heavily reliant on gas for heating, even though electric heating (including heat pumps) is more prevalent than in the domestic sector<sup>15</sup>. Heat networks have seen two decades of expansion (starting from a rather low base) and a large majority are gas-fed, often with combined heat and power. Data on their carbon content has often not been reported, but many networks are understood to operate with high distribution losses.

The current state of UK residential buildings and possible pathways to decarbonisation are discussed in a report prepared for the CCC<sup>16</sup>. The Net Zero scenarios from the CCC and from National Grid ESO all assume a contribution from improving the energy efficiency of the existing stock, and it is generally acknowledged that this is required to allow heat pumps to operate more efficiently, reduce demand and support demand management, and reduce energy costs for consumers.

There is still significant debate about the right level of energy efficiency improvement which should be targeted. Policy in this area is patchy and is often focused on individual measures rather than whole-building approaches and deep retrofit. There are few incentives for retrofit – often only for individual measures or stop-start policies that affect trust among consumers and supply chains. The rate of installation of insulation measures has dropped in the past few years<sup>17</sup>.

Retrofit works are mostly subject to 20% VAT (sales tax), while new build construction is zero-VAT rated. One significant area of policy progress, however, is the expected introduction of operational ratings for non-domestic buildings (starting with commercial offices), which would rate buildings for their actual measured performance rather than theoretical asset ratings.

Examples of low-energy retrofits tend not to be available in a single resource, but some can be found from the Passivhaus Trust (Enerphit standard) and the AECB, both mostly for homes. The Better Buildings Partnership has examples for the commercial office sector, often focusing on energy management rather than deep retrofit but still demonstrating the potential for energy savings in that sector.

<sup>12</sup> <https://www.ofgem.gov.uk/publications/riio-2-strategic-innovation-fund-possible-innovation-challenges-round-1>

<sup>13</sup> <https://www.gov.uk/government/organisations/innovate-uk>

<sup>14</sup> <https://www.gov.uk/guidance/energy-innovation>

<sup>15</sup> BEIS, Clean Growth – Transforming Heating, December 2018

<sup>16</sup> <https://www.thccc.org.uk/publication/development-of-trajectories-for-residential-heat-decarbonisation-to-inform-the-sixth-carbon-budget-element-energy/>

<sup>17</sup> CCC 2021 Progress Report to Parliament, Figure 3.5

### 3.2. New Buildings

A draft Bill<sup>18</sup> is being developed to enact a step change in the quality and safety of buildings, especially high-rise residential buildings and other high-risk buildings.

There is a shortage of housing in the UK, especially of more affordable housing in areas of higher employment. This has been the subject of repeated policy developments over the last twenty years. Housing is largely a devolved issue within the UK<sup>19</sup> and detailed planning is a regional and local matter.

Within England, new housing will have to achieve low-carbon efficiency and emissions standards by 2025<sup>20</sup>, which effectively bans the use of new gas boilers and mandates the use of heat-pumps, electric heating or other low-carbon heating systems. This will have a major effect on housing development. Proposals are similar for non-domestic buildings, though will probably be phased over a longer period with flexibility for a wider range of heating and hot water systems.

Through combination of a significant increase in renewables generation by 2030, charging of suppliers by the half-hourly usage of their customers, and the development of new technologies to test the as-built performance of buildings (e.g. low-pressure air testing, heat transfer coefficient estimates through smart meters), policies aim to transform both the supply chain and the user experience. Recent policies have been proposed to address the carbon content of new and expanding networks; as starting point, this could mean that financial support would only be available for networks which are as low-carbon (or lower) than a local air source heat pump system<sup>21</sup>.

Case studies of recent low-energy buildings were produced by the Green Construction Board in 2019<sup>22</sup>, in response to a (now dropped) government ambition to halve energy use in new buildings. This covers schools, offices, and homes.

## 4. Industry

### 4.1. Chemicals

The UK Chemicals Industry (including pharmaceuticals) is the largest industrial energy user, accounting for ~15% of industrial energy use<sup>23</sup>.

11% of direct emissions in chemicals are from the process and the rest from combustion to provide heat. Natural gas is the dominant fuel. 25% of direct emissions are from olefins production, 13% from ammonia and the rest are split across a wide variety of basic organic (for example acrylonitrile or acetic acid) and inorganic chemicals (for example soda ash or titanium dioxide). Indirect emissions from electricity use are just under 40% of total attributable emissions. The most immediate opportunity for decarbonisation after efficiency gains and further electrification is the capture of CO<sub>2</sub> from ammonia production, as part of one or more industrial CCS clusters.

The global chemical industry has multiple inputs to enabling a low-carbon economy, for example in production of insulating materials or technologies for producing low-carbon ammonia as a potential fuel for shipping. Requirements for chemicals will change – adapting to the future global economy is not just about reducing emissions from existing operations<sup>24</sup>. The industry has agreed an action plan<sup>25</sup> with the Department for Business, Energy and Industrial Strategy – building on its Industrial Decarbonisation and Energy Efficiency Roadmap<sup>26</sup>.

Decarbonisation in the chemical industry is entangled with national strategies for industrial clusters, low-carbon hydrogen production, and progress with decarbonising electricity and ensuring consistent baseload electricity

<sup>18</sup> <https://www.gov.uk/government/news/explained-the-draft-building-safety-bill>

<sup>19</sup> <https://www.gov.uk/government/publications/homes-england-strategic-plan-201819-to-202223>, <https://www.gov.scot/publications/housing-2040-2/>, [https://www.birmingham.gov.uk/info/20054/local\\_plan\\_documents/78/birmingham\\_development\\_plan,...](https://www.birmingham.gov.uk/info/20054/local_plan_documents/78/birmingham_development_plan,...)

<sup>20</sup> <https://www.gov.uk/government/consultations/the-future-homes-standard-changes-to-part-l-and-part-f-of-the-building-regulations-for-new-dwellings>

<sup>21</sup> BEIS Green Heat Network fund. The details are still to be confirmed and the calculation may use marginal carbon factors.

<sup>22</sup> Green Construction Board, Buildings Mission Background Report, 2019  
<https://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2019/05/GCB-Energy-Mission-Report-300419-FINAL.pdf>

<sup>23</sup> <https://www.cia.org.uk/Portals/0/Documents/Publications/20150217%20CIA%20facts%20and%20figures%202015.pdf?ver=2017-01-09-143806-033>

<sup>24</sup> [https://www.cia.org.uk/Portals/0/Documents/Publications/Low%20carbon%20brochure\\_2015\\_MR.PDF?ver=2017-01-09-143808-563](https://www.cia.org.uk/Portals/0/Documents/Publications/Low%20carbon%20brochure_2015_MR.PDF?ver=2017-01-09-143808-563)

<sup>25</sup> [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/651230/chemicals-decarbonisation-action-plan.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/651230/chemicals-decarbonisation-action-plan.pdf)

<sup>26</sup> <https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050>

supply at competitive prices. International discussions about cross-border embedded carbon accounting are important to progress, given the significance of trade to the production and use of chemicals in the UK.

## 4.2. Steel

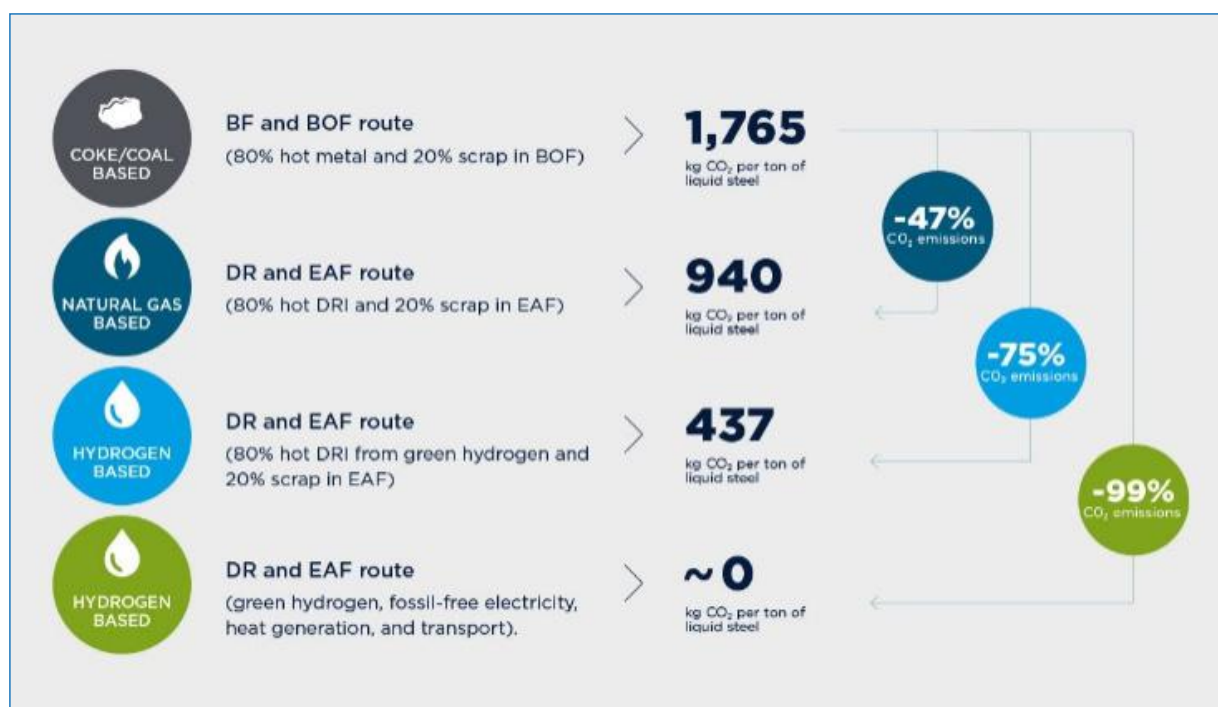
The UK Steel Industry is responsible for 2% of the entire UK greenhouse gas emissions (13.5% of entire UK manufacturing GHG output). Over the past 50 years the production of steel in the UK has decreased from c. 30MT/pa to under 10MT/pa. The majority of this is via the more carbon intensive BF/BOS processes however significant improvements have been made over that period to reduce the carbon intensity of the steel manufacturing process.

Steel is 100% recyclable either via the Basic Oxygen or Electric Arc Steelmaking route, however some of the key decarbonisation issues facing the industry at present come from the grades of steel being produced and the scrap sources available, alongside energy intensity concerns for decarbonisation pathways. The different types of scrap can have an impact on both the overall process and subsequent product quality. Product quality concerns tend to be driven by the scrap residuals such as copper and tin, whereas some of the dusts generated can impact the environmental performance of the plant.

UK finished steel consumption is stable at approximately 10MT/pa. It must be noted that not all of the grades consumed can be produced within the UK thus there is a trade deficit within our current asset configuration. Alongside this, currently a significant volume of steel scrap is exported from the country every year.

Current market conditions drive producers to maximise scrap consumption where possible, leading to a reduction in the carbon intensity of primary production, as less Liquid Iron is required per ton of finished steel. This market position will further evolve as steel grades are developed which are acceptable to customers with a higher residual content and the global steelmaking market decarbonises with major global iron ore suppliers decarbonising their production processes and changing their products being offered.

A technology development pathway towards net zero carbon emissions for steel has been proposed by Primetals shown in the figure below. This transition requires a stepwise increase in the electricity consumption within the regions that these industrial areas are located; thus, a holistic review of energy generation and co-industrial location needs to be developed. Such a pathway would however enable companies to transition towards lower carbon intensive technologies in a managed manner.



**Fig. 5.** Comparing CO<sub>2</sub> emissions of different process routes for liquid steel. Calculations are based on emissions from electricity production on European OECD level

Significant investment support had been made available by the government for decarbonisation-based projects for the steel industry (£250m Clean Steel Fund) and a number of other funding streams have been made available from the UK government for industrial clusters centred in steelmaking regions<sup>27, 28</sup>. Whilst these large-scale funds are very welcome, the full cost of decarbonisation for the UK steel industry is expected to be an order of magnitude higher; thus, long term capital support mechanisms are also required.

The UK government published a Hydrogen Roadmap<sup>29</sup> in August 2021 covering further support for maturing Hydrogen generation and Carbon Capture technologies which are critical to support business decision making on which technology to progress towards. A UK industrial decarbonisation policy is expected to be published within Q4 2021 which further enables the UK steel industry a basis to refine the UK decarbonisation roadmap which is being developed by the UK Steel Council.

---

<sup>27</sup> <https://www.zerocarbonhumber.co.uk/the-vision/>

<sup>28</sup> <https://www.swic.cymru/>

<sup>29</sup> [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/1011283/UK-Hydrogen-Strategy\\_web.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf)

Please, note that in tables  
D=Withheld to avoid disclosing data for individual establishments.  
Q=Withheld because Relative Standard Error (RSE) is greater than 50 percent

Table of Contents

1.	National energy profile 2019	434
2.	Energy perspectives 2030 - 2050	438
3.	Building sector	445
3.1.	Existing buildings	445
3.2.	New buildings	449
4.	Industry	450
5.	Case study	453

## 1. National energy profile 2019

### US Total yearly consumption: final energy, electricity (TWh)

Year	Energy Consumption (TWh)	Electricity Consumption (TWh)	Elec/Energy (%)
1990	15 043.82	2 923.92	19.4
1995	16 023.04	3 370.98	21.0
2000	17 983.19	3 857.46	21.5
2005	18 178.41	4 049.93	22.3
2010	17 595.85	4 143.41	23.5
2015	17 568.83	4 128.51	23.5
2019	18 473.97	4 055.51	22.0

**Table 1.** US Total yearly consumption: final energy, electricity (TWh)

**Source:** IEA World Energy Balances <https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances>  
IEA Data Services <https://www.iea.org/data-and-statistics/data-products>; and <https://www.iea.org/countries/united-states>

During this period, the population steadily increased from 250 million to 329 million (+30%). Energy consumption also rose steadily through 2005 (+20.8%), then fell and remained lower for about a decade. The 2008 financial crisis and ensuing recession played some role in the decreased energy use during this time period. The recession also precipitated the American Recovery and Reinvestment Act of 2009 (ARRA), which provided USD 70-80 billion in tax credits and direct spending on clean energy and clean transport. The result is a 22.8% increase in final energy consumption from 1990 to 2019, but 2019 final energy consumption is 1.6% higher than 2005 levels.

Electricity use increased 38.7% from 1990 to 2019, yet slightly decreasing from 2010 to 2019 (by 2.1%). 2010 and 2015 had both the highest electricity consumption and lowest energy consumption levels.

Electricity consumption as a proportion of final energy consumption grew from 1990 to 2019, but not as dramatically as some other OECD countries, and with slight decrease from 2015 to 2019.

### Per capita yearly final energy and electricity consumptions (MWh)

Year	Energy (MWh/capita)	Electricity (MWh/capita)
1990	60.27	11.69
1995	60.17	12.64
2000	63.73	13.66
2005	61.51	13.68
2010	56.89	13.38
2015	54.79	12.86
2019	56.28	12.28

**Table 2.** Per capita yearly final energy and electricity consumptions (MWh)

**Sources:** IEA World Energy Balances <https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances>;  
IEA Data Services <https://www.iea.org/data-and-statistics/data-products>

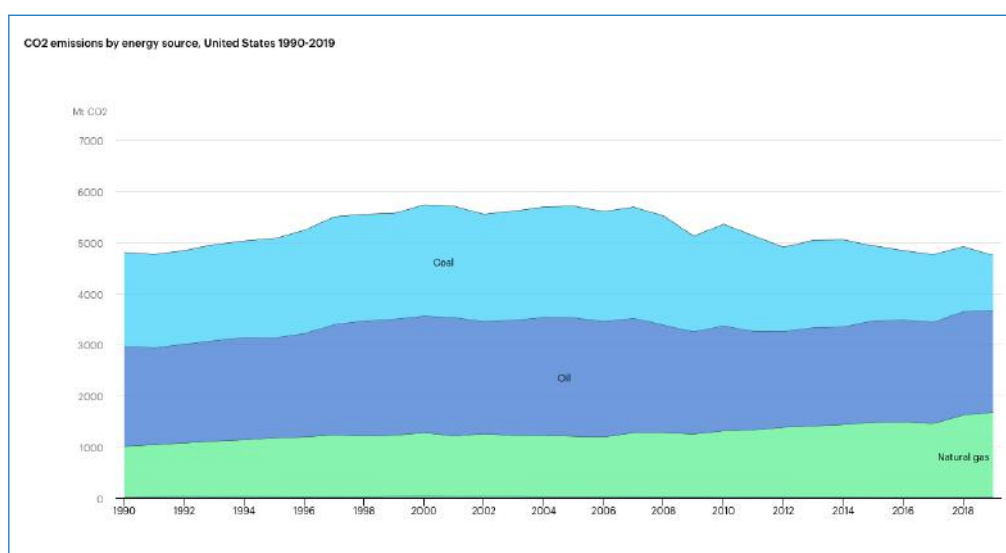
### Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>), total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)

Year	Total CO <sub>2</sub> Emissions (MtCO <sub>2</sub> )	CO <sub>2</sub> Emissions from electricity (MtCO <sub>2</sub> )	CO <sub>2</sub> emissions per capita
1990	4 803.00	1 901 (1825)	19.20
1995	5 073.84	2 167 (1957)	19.03
2000	5 729.82	2 542 (2306)	20.29
2005	5 703.15	2 523 (2411)	19.27
2010	5 352.05	2 346 (2270)	17.28
2015	4 928.61	1 985 (1911)	15.36
2019	4 744.50	1 699 (1617)	14.40

**Table 3.** Total CO<sub>2</sub> emissions, CO<sub>2</sub> emissions from electricity production (MtCO<sub>2</sub>), total CO<sub>2</sub> emissions per capita (tCO<sub>2</sub>)

Data for total CO<sub>2</sub> emissions: <https://www.iea.org/data-and-statistics/data-browser/?country=USA&fuel=CO2%20emissions&indicator=TotCO2>  
 Data for CO<sub>2</sub> emissions from electricity: IEA Greenhouse Gas Emissions from Energy <https://www.iea.org/data-and-statistics/data-product/co2-emissions-from-fuel-combustion>. Parenthetical numbers are U.S. EIA-reported CO<sub>2</sub> emissions from electricity sector, as IEA binds electricity and heat producers together, thus producing some inconsistency. EIA Source is Table 11.6 from February 2022 Monthly Energy Review.  
 Data for CO<sub>2</sub> emissions per capita: <https://www.iea.org/data-and-statistics/data-browser?country=USA&fuel=CO2%20emissions&indicator=CO2PerCap>

### CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)



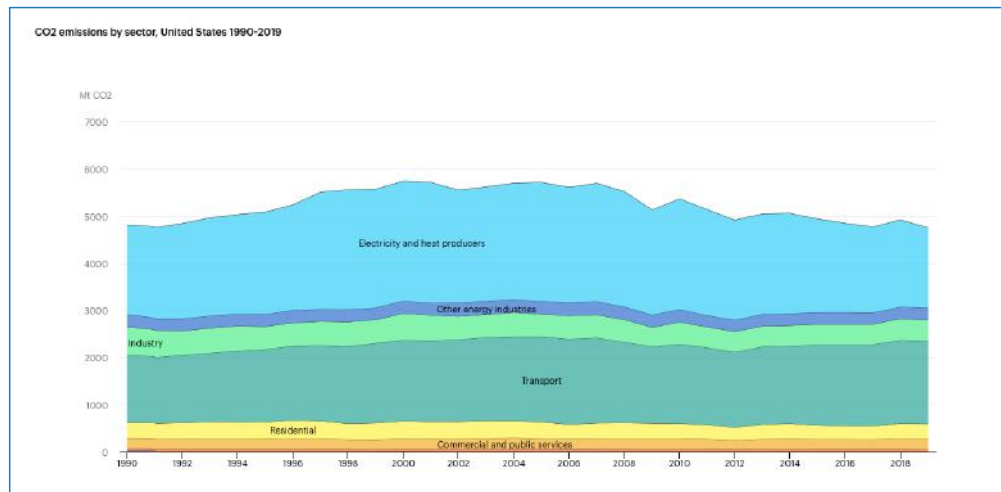
**Fig. 1.** CO<sub>2</sub> emissions by fossil energy source (MtCO<sub>2</sub>)

Data from IEA, Data & Statistics

<https://www.iea.org/data-and-statistics/data-browser?country=USA&fuel=CO2%20emissions&indicator=CO2BySource>

US energy-related CO<sub>2</sub> emissions peaked in 2007, according to the U.S. EIA. US energy-related CO<sub>2</sub> emissions from coal have significantly reduced; the U.S. EIA reports a decline of more than 50% from 2007 to 2019, which is more than a billion metric tonnes. This is largely due to coal no longer being the most economic choice in many regions. US energy-related CO<sub>2</sub> emissions from oil have been slightly decreasing. The U.S. EIA indeed reports a decline of 8.5% from 2007 to 2019. US energy-related CO<sub>2</sub> emissions from natural gas have been increasing, which is mainly due to increased supply and therefore competitive natural gas prices; the U.S. EIA reports 35.6% increase from 2007 to 2019. EIA (U.S. Energy Information Administration). 2020. "U.S. Energy-Related Carbon Dioxide Emissions, 2019." Washington, DC: U.S. Energy Information Administration <https://www.eia.gov/environment/emissions/carbon/archive/2019/>

## CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)

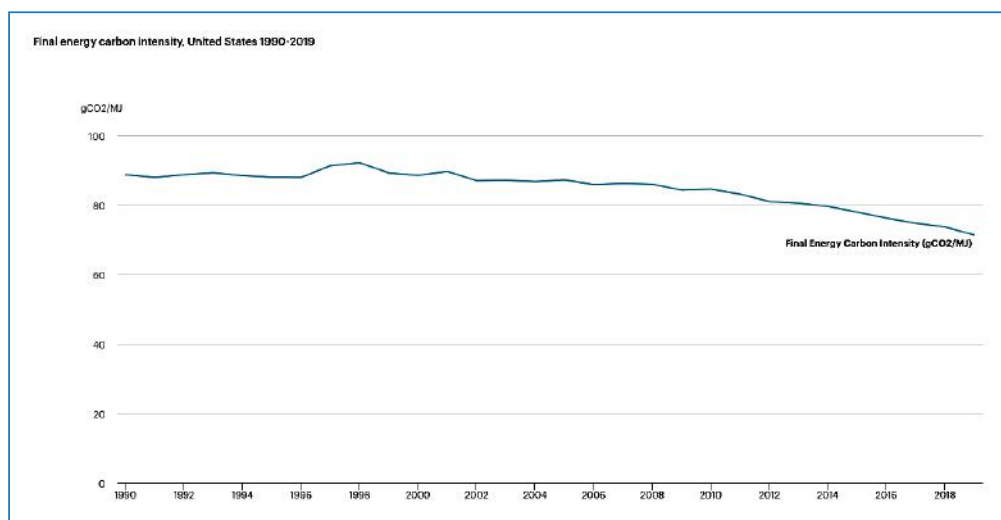


**Fig. 2.** CO<sub>2</sub> emissions by sector (MtCO<sub>2</sub>)

Data from IEA, Data & Statistics

<https://www.iea.org/data-and-statistics/data-browser?country=USA&fuel=CO2%20emissions&indicator=CO2BySector>

## Final energy carbon intensity: gCO<sub>2</sub>/MJ and gCO<sub>2</sub>/kWh (1 Megajoule = 0.27778 Kilowatt hours)



**Fig. 3.** Final energy carbon intensity, United States, 1990-2019, gCO<sub>2</sub>/MJ

Data from IEA, Data & Statistics <https://www.iea.org/data-and-statistics/data-browser?country=USA&fuel=CO2%20emissions&indicator=FECI>

Year	Final Energy Carbon Intensity (gCO <sub>2</sub> /MJ)	Final Energy Carbon Intensity (gCO <sub>2</sub> /KWh)
1990	88.69	319.2814
1995	87.96	316.6535
2000	88.51	318.6335
2005	87.15	313.7375
2010	84.49	304.1616
2015	77.93	280.5458
2019	71.34	256.8219

**Table 4.** Final energy carbon intensity, United States, 1990-2019, both in gCO<sub>2</sub>/MJ and gCO<sub>2</sub>/KWh

The falling carbon intensity of energy in the United States has largely come from decreases in the consumption of fuels with high carbon contents. Part of this change comes from the continuing trend of natural gas and renewables displacing coal for electric power generation, both of which have lower or zero carbon content.

### Electricity Carbon intensity: gCO<sub>2</sub>/kWh

Year	Carbon intensity of electricity production (gCO <sub>2</sub> /kWh)
1990	
1991	
1992	606.832
1993	601.2016
1994	599.9504
1995	598.0736
1996	603.0784
1997	663.7616
1998	656.2544
1999	640.6144
2000	625.6
2001	661.0
2002	588.6
2003	591.4
2004	589.2
2005	586.2
2006	562.8
2007	571.6
2008	554.4
2009	525.9
2010	530.5
2011	510.8
2012	487.6
2013	489.4
2014	485.7
2015	455.7
2016	433.2
2017	421.1
2018	411.1
2019	383.2

**Table 5.** Electricity carbon intensity: gCO<sub>2</sub>/kWh

1992-2000 data back-calculated using carbon intensity of power indexed data from

<https://www.iea.org/data-and-statistics/data-browser?country=USA&fuel=CO2%20emissions&indicator=CO2IntensityPower>

and “Year 2000” data from IEA, *Development of CO<sub>2</sub> emission intensity of electricity generation in selected countries, 2000-2020*, IEA, Paris<sup>1</sup>.

2000-2019 data from: IEA, *Development of CO<sub>2</sub> emission intensity of electricity generation in selected countries, 2000-2020*, IEA, Paris

<https://www.iea.org/data-and-statistics/charts/development-of-co2-emission-intensity-of-electricity-generation-in-selected-countries-2000-2020>

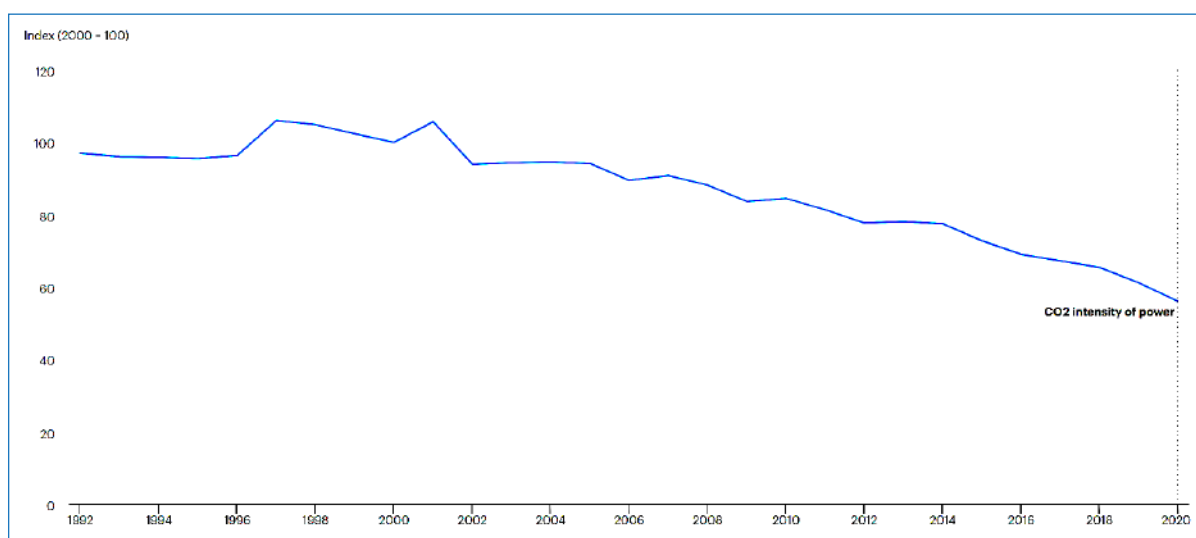


Fig. 4. Carbon intensity of the power sector

As displayed in the above graph from IEA, the carbon intensity of the power sector has been steadily decreasing since the early 2000s.

The U.S. Energy Information Administration (EIA) reports the 2020 carbon intensity of electricity generation in the United States to be 0,386 kg of CO<sub>2</sub> emissions per KWh, which equates to about 385.55 gCO<sub>2</sub>/KWh.

## 2. Energy perspectives 2030 - 2050

If possible, give the national perspectives for 2030 and 2050 or the roadmap to 2030 and 2050 if they exist.

### National roadmaps regarding energy production and GHG

The United States does not have a national roadmap for either energy production or GHG emissions. In September 2020, the U.S. Department of Energy published a Fossil Energy Roadmap, pursuant to a congressional request in the explanatory statement accompanying the Consolidated Appropriations Act, 2018. However, this Roadmap is a collection of research and development objectives for fossil energy, not a pathway to decreasing emissions.

The U.S. Energy Information Administration (EIA) 2021 Annual Energy Outlook projects energy production through to 2050. 2020, 2030, and 2050 values are presented below.

Production	2020	2030	2050	Average annual increase (+) or decrease (-) in percent 2020-2050
(quadrillion Btu)				
Crude oil and lease condensate	23.87	28.57	26.64	+0.4%
Natural gas plant liquids	6.58	7.90	8.05	+0.7%
Dry natural gas	35.14	39.28	44.58	+0.8%
Coal	10.80	10.14	9.08	-0.6%
Nuclear / Uranium	8.21	6.59	6.21	-0.9%
Conventional hydroelectric power	2.53	2.43	2.29	-0.3%
Biomass	4.47	4.89	5.39	+0.6%
Other Renewable energy	4.43	9.52	14.11	+3.9%
Other	0.69	0.65	0.71	+0.1%
Total	96.72	109.97	117.08	+0.6%

Table 6. Projected annual energy production through to 2050

The EIA 2021 Annual Energy Outlook projects GHG emissions through 2050. 2020, 2030, and 2050 values below:

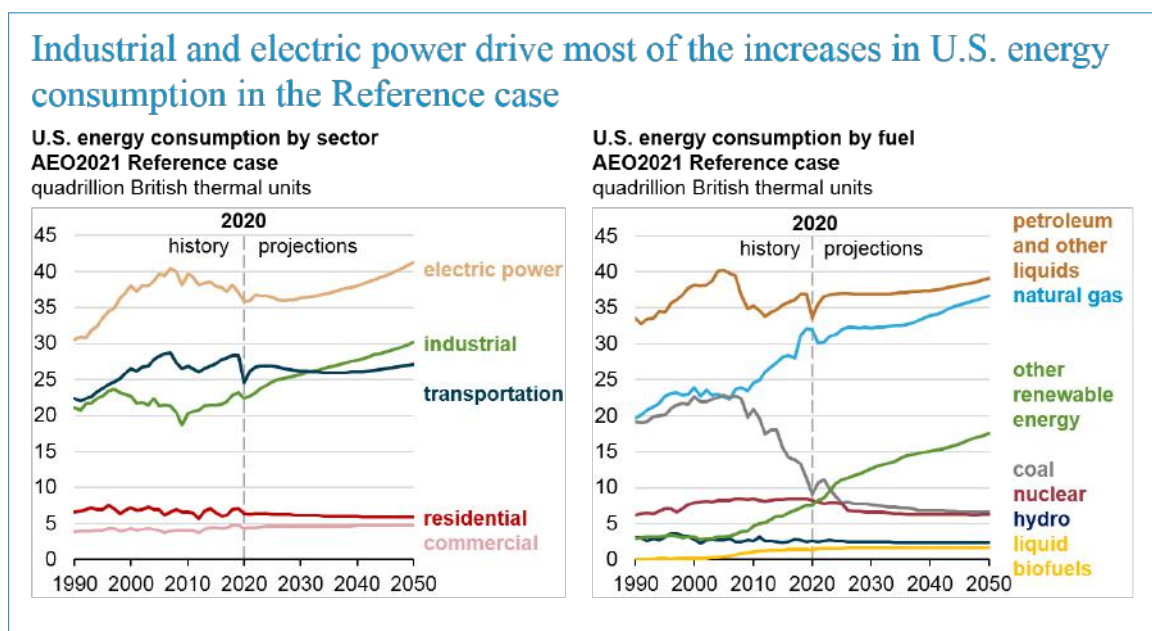
CO <sub>2</sub> Emissions	2020	2030	2050	Average annual increase (+) or decrease (-) in percent 2020-2050
(million metric tonnes carbon dioxide)	4 562.5	4 583.5	4 806.9	+ 0.2%

*Table 7.* Projected annual GHG emissions through to 2050

## Roadmap for the energy mix

The United States does not have a national roadmap for the energy mix. In November 2016, the Obama administration put forth its United States Mid-Century Strategy for Deep Decarbonization; this strategy was not continued by the following administration. The U.S. National Academies published a decarbonization report in 2021 focusing on actions necessary in the 2020s to put the United States on the path to net-zero energy system, Accelerating Decarbonization of the U.S. Energy System.

The US Energy Information Administration (EIA) 2021 Annual Energy Outlook projects the energy mix through to 2050 as below:



*Fig. 5.* Past and projected energy consumption through to 2050 by sector (left) and by fuel type (right)

*Source:* U.S. Energy Information Administration Annual Energy Outlook 2021 (AEO2021) [www.eia.gov/aeo](http://www.eia.gov/aeo)

## Roadmap for the GHG emissions (country, per capita)

There is no national GHG emissions roadmap administered or enforced by the U.S. federal government. However, many states have established emissions targets and roadmaps to reach those goals, often with legally binding elements. Several states have also joined into the Regional Greenhouse Gas Initiative (RGGI), a mandatory, market-based greenhouse gas pollution reduction programme.

The EIA 2021 Annual Energy Outlook projects energy related GHG emissions per sector and per capita:

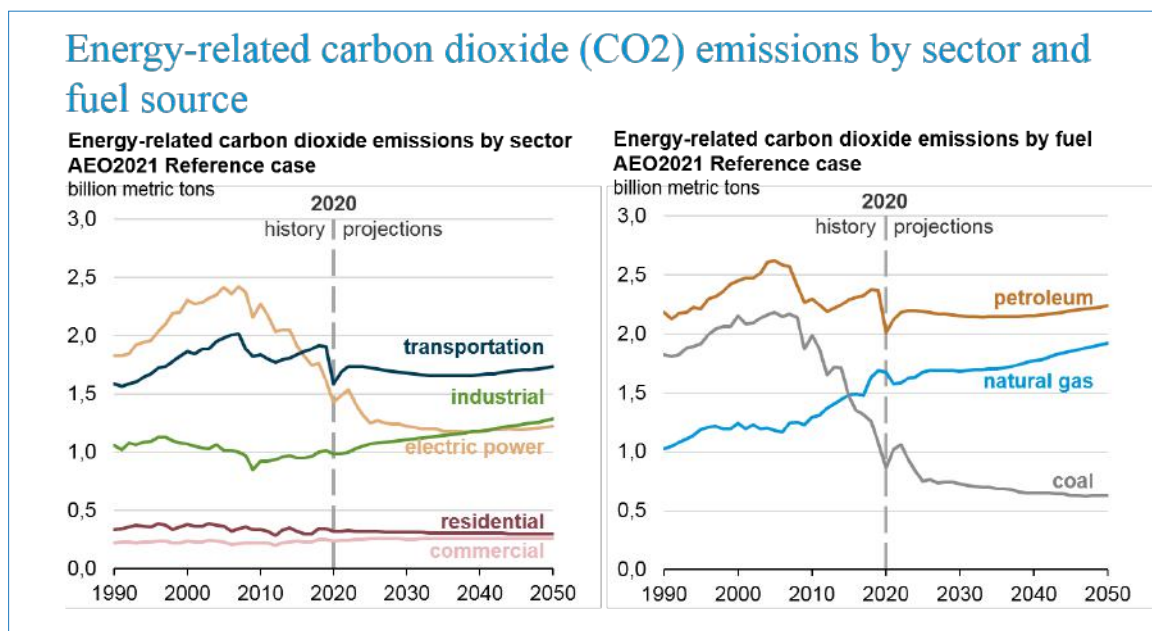


Fig. 6. Past and projected CO<sub>2</sub> emissions through to 2050 by sector (left) and by fuel type (right)

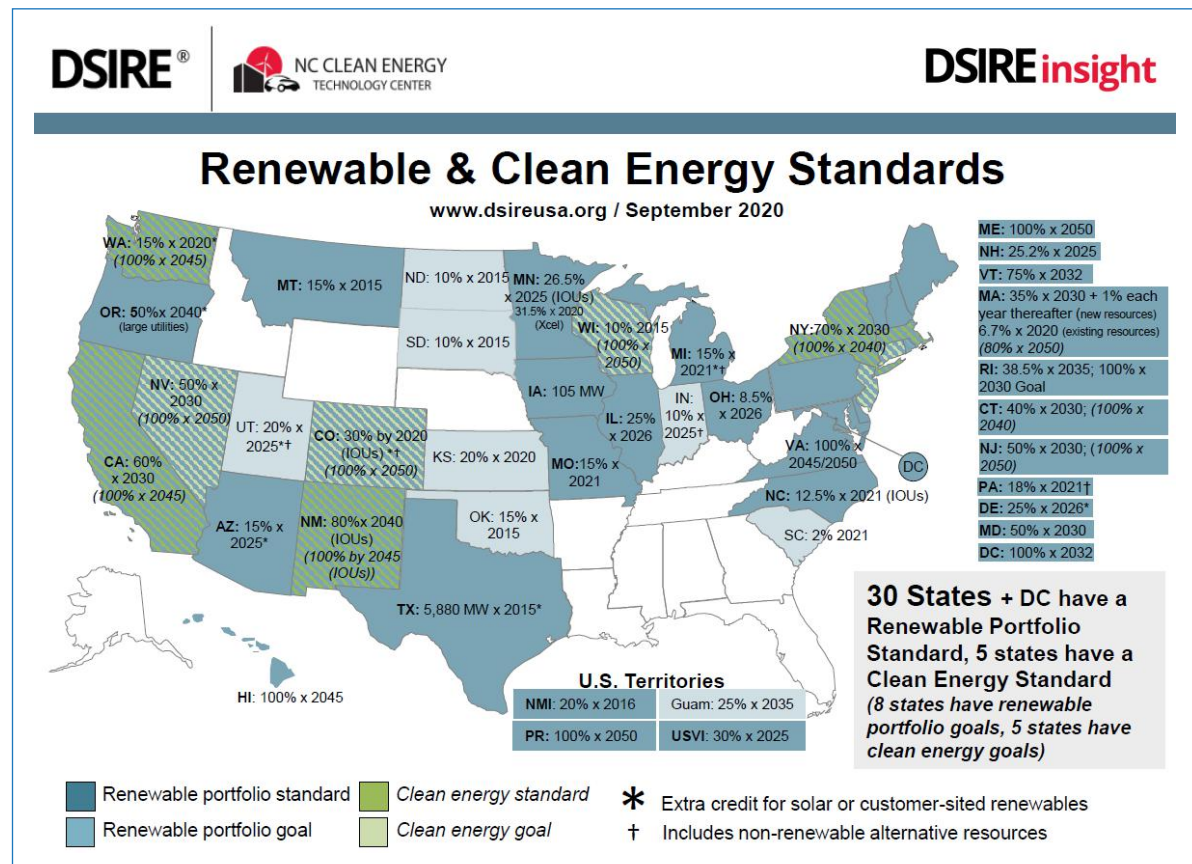
Source: U.S. Energy Information Administration Annual Energy Outlook 2021 (AEO2021) [www.eia.gov/aeo](http://www.eia.gov/aeo)

	2020	2030	2050	
CO <sub>2</sub> Emissions Per Capita (tonnes CO <sub>2</sub> per person)	13.8	13.0	12.4	-0.3%/yr

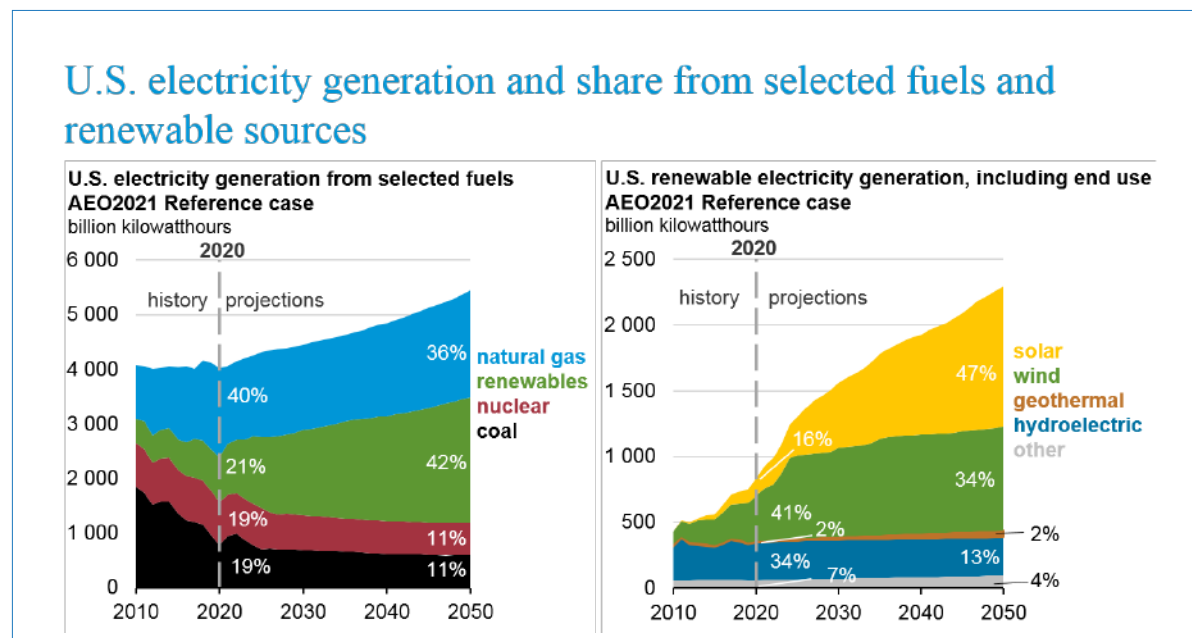
Table 8. CO<sub>2</sub> emissions per capita

## Roadmap for the electricity mix

There is no national roadmap for the electricity mix administered or enforced by the U.S. federal government. However, many states have established renewable portfolio standards or carbon-free electricity targets and roadmaps to reach those goals, often with legally binding elements (see figure below from the NC Clean Energy Technology Centre and the Database of State Incentives for Renewables & Efficiency – DSIRE, which shows the aimed-for share of renewable energies by a given year (Example: New Mexico: 80% by 2040 and 100% by 2045). In April 2021, the Biden administration set a goal for 100% carbon-free electricity generation by 2035. In September 2021, the Biden administration set a goal to produce 50% of US electricity via solar power by 2050. Neither of these has legal enforcement capability and both must wait for legislation from Congress or regulation from authorised entities.



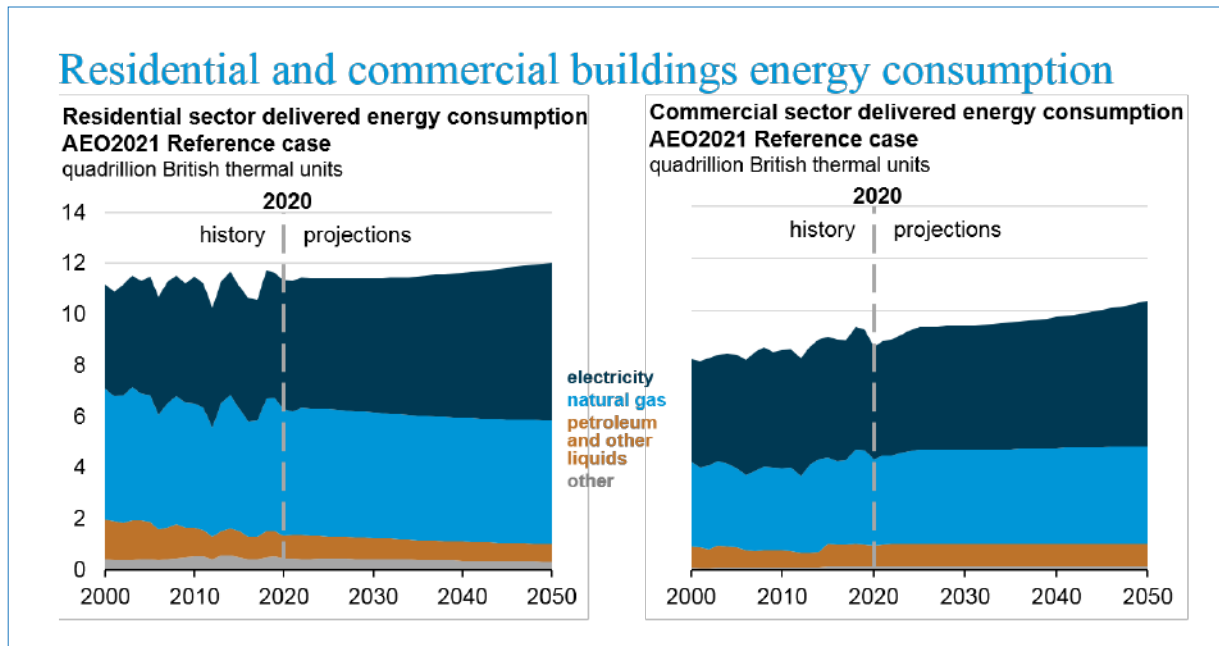
**Fig. 7.** Renewable & Clean Energy Standards in the 30 States + DC by type and percentage  
The EIA 2021 Annual Energy Outlook projects the electricity mix in the following graphs:



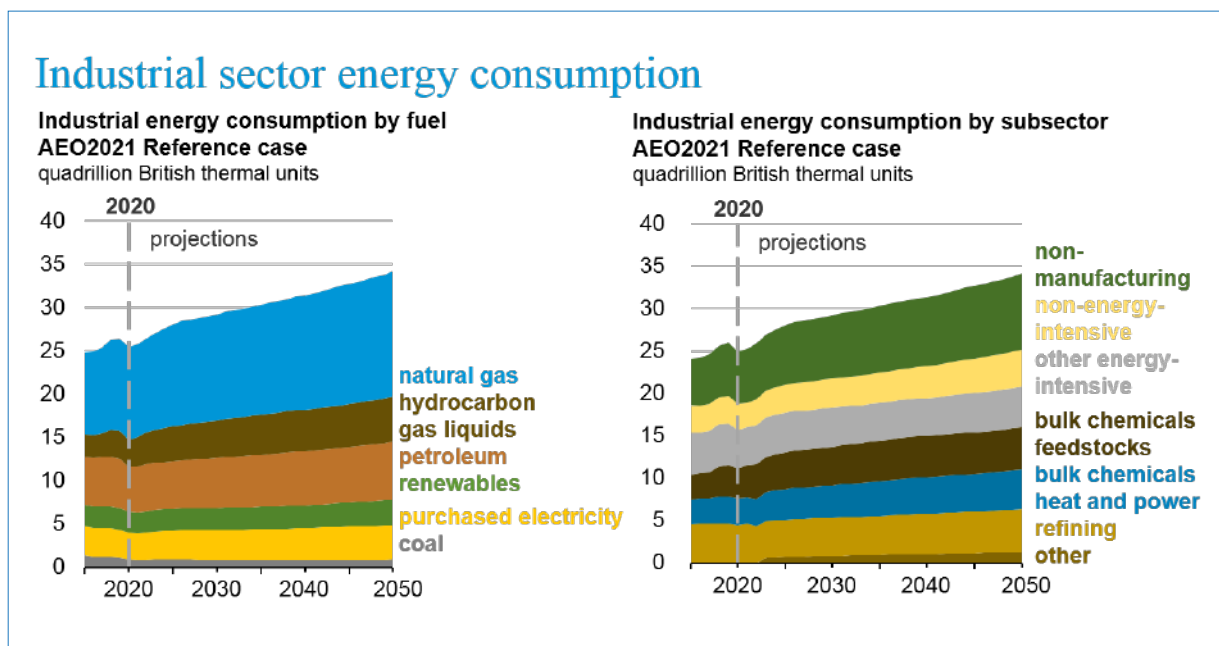
**Fig. 8.** Past and projected electricity generation through to 2050 by fuel type (left) and by renewable source (right)  
**Source:** U.S. Energy Information Administration Annual Energy Outlook 2021 (AEO2021) [www.eia.gov/aeo](http://www.eia.gov/aeo)



The EIA 2021 Annual Energy Outlook projects energy production and energy consumption out to 2050. A graphical representation for consumption up to 2050 for the residential, commercial, industrial, and transport sectors is provided below:



**Fig. 10.** Past and projected energy consumption through to 2050 by type of source for the residential sector (left) and the commercial sector (right)  
Source: U.S. Energy Information Administration Annual Energy Outlook 2021 (AEO2021) [www.eia.gov/aeo](http://www.eia.gov/aeo)



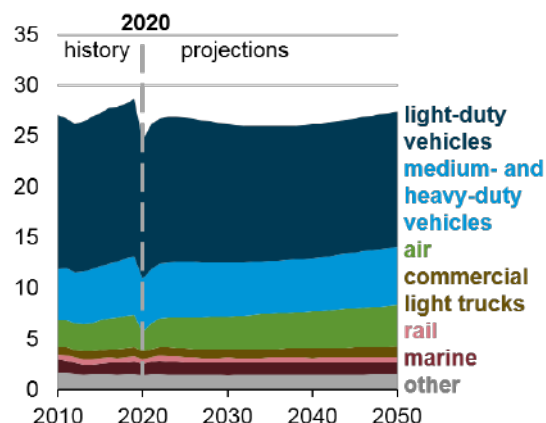
**Fig. 11.** Past and projected industrial sector energy consumption through to 2050 by fuel type (left) and by industrial sub-sector (right)  
Source: U.S. Energy Information Administration Annual Energy Outlook 2021 (AEO2021) [www.eia.gov/aeo](http://www.eia.gov/aeo)

## Transportation sector energy consumption

### Transportation sector consumption by mode

#### AEO2021 Reference case

quadrillion British thermal units



### Transportation sector consumption by fuel

#### AEO2021 Reference case

quadrillion British thermal units

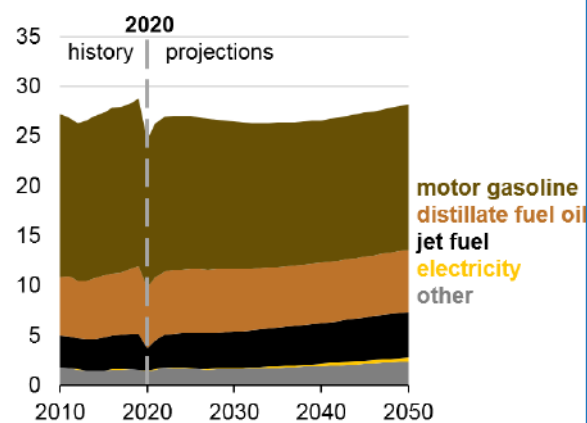


Fig. 12. Past and projected transport sector energy consumption through to 2050 by transport mode (left) and fuel type (right)

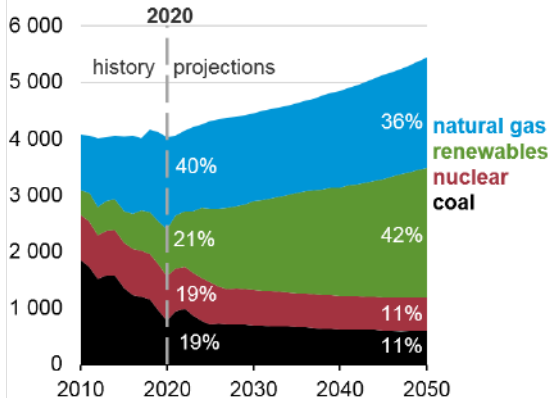
Source: U.S. Energy Information Administration Annual Energy Outlook 2021 (AEO2021) [www.eia.gov/aeo](http://www.eia.gov/aeo)

## U.S. electricity generation and share from selected fuels and renewable sources

### U.S. electricity generation from selected fuels

#### AEO2021 Reference case

billion kilowatthours



### U.S. renewable electricity generation, including end use

#### AEO2021 Reference case

billion kilowatthours

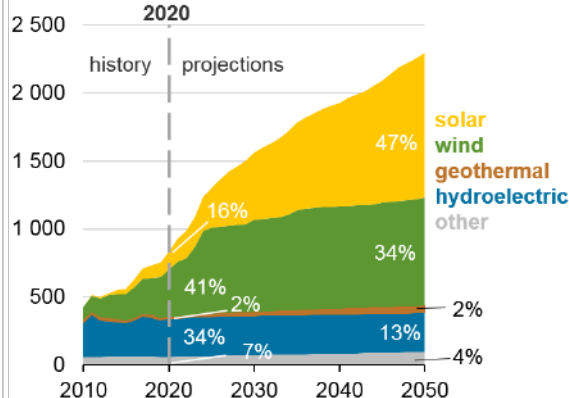


Fig. 13. Past and projected electricity generation through to 2050 by fuel type (left) and by renewable source (right) [same as Fig. 8]

Source: U.S. Energy Information Administration Annual Energy Outlook 2021 (AEO2021) [www.eia.gov/aeo](http://www.eia.gov/aeo)

### 3. Building sector

#### 3.1. Existing buildings

##### Energy balance 2019 (energy sources to end-uses)

The U.S. EIA conducted its last Residential Energy Consumption Survey (RECS) in 2015. According to the EIA's website, data for the 2021 RECS was collected in 2020-21, and results are to be released in late 2021 / 2022.

The U.S. EIA did its last Commercial Building Energy Consumption Survey (CBECS) in 2012. Preliminary building characteristics for the 2018 CBECS are available now. According to the EIA website, microdata will be available in November 2021, and consumption and expenditures information will be available starting in spring 2022.

##### Energy partition between single houses, apartments buildings and office buildings

The 2015 RECS found that the average single family detached home used 94.6 million Btu per year, single family attached home used 70, apartment with 2-4 units used 53.5, apartment with 5+ units used 34.2, and mobile homes used 59.8. See *Table CE3.1* "Annual household site end-use consumption in the U.S.—totals and averages, 2015" below:

Table CE3.1 Annual household site end-use consumption in the USA —totals and averages, 2015													
Housing unit type	Total housing units (million)	Total site energy consumption (trillion Btu)						Average site energy consumption (million Btu per household using the end use)					
		Total	Space heating	Water heating	Air conditioning	Refrigerators	Other	Total	Space heating	Water heating	Air conditioning	Refrigerators	Other
Single-family detached	73.9	6 991	3 201	1 185	586	221	1 798	94.6	44.9	16.1	8.9	3.0	24.3
Single-family attached	7.0	491	228	95	33	16	119	70.0	34.1	13.5	5.4	2.3	17.0
Apartments in buildings with 2–4 units	9.4	503	197	136	25	17	129	53.5	22.2	14.5	3.3	1.8	13.7
Apartments in buildings with 5 or more units	21.1	724	183	234	51	35	220	34.2	9.7	11.1	2.9	1.7	10.4
Mobile homes	6.8	406	136	96	36	14	124	59.8	22.1	14.1	6.2	2.2	18.3

**Table 10.** Total and average energy consumption by housing type and by type of use

The 2012 CBECS found the average office building is responsible for 1,226 million Btu per year of energy use, with major fuel energy intensity of 77.8 thousand Btu/square foot. See “Table PBA3. Sum of major fuel consumption totals and gross energy intensities by building activity subcategories, 2012” below:

Sum of major fuel consumption totals and gross energy intensities by building activity subcategories:

				Sum of major fuel consumption					
	All buildings						Distribution of building-level intensities (thousand Btu/square foot)		
	Number of buildings (thousand)	Total floor-space (million square feet)	Floor-space per building (thousand square feet)	Total (trillion Btu)	per building (million Btu)	per square foot (thousand Btu)	25th per-centile	Median	75th per-centile
All buildings	5 557	87 093	15.7	6 963	1 253	80.0	18.9	45.9	89.0
Office	1 012	15 952	15.8	1 241	1 226	77.8	32.6	52.7	80.2

**Table 11.** Buildings – Total and average Floor spaces and energy consumption - total, per surface area, and distribution – all buildings and Office space

### Which systems are mostly used for heating? Local systems (Furnaces, electric heating, heat pumps, solar thermal panels, geothermal systems, etc.)?

Local systems service 88% of residential buildings – mostly central warm-air furnaces and heat pumps (exact numbers in *Table HC6.1, 2015 RECS*, below).

Main heating equipment (including all fuels) [EIA 2015 RECS Table HC6.1]	Number of housing units, millions
Total	118.2
Central warm-air furnace	70.1
Heat pump	13.4
Steam or hot water system	9.1
Built-in electric units	9.2
Built-in oil or gas room heater	3.1
Portable electric heaters	3.0
Heating stove burning wood	2.7
Built-in pipeless furnace	1.1
Fireplace	0.8
Some other equipment	0.6
Do not use heating equipment	5.1

**Table 12.** Main heating equipment in residential buildings

Local systems service 99.1% of commercial buildings – mostly packaged heating units and space heaters, followed by furnaces, heat pumps, and boilers (*Table B26, 2012 CBECS*, below).

Heating equipment (more than one may apply [EIA 2012 CBECS Table B26])	Number of housing units, millions
Total	5 557
Heat pumps	628
Furnaces	755
Individual space heaters	1 247
District heat	48
Boilers	544
Packaged heating units	2 802
Other	62

*Table 13.* Main heating equipment in commercial buildings

- **Heat networks (hot water, steam). In this case, which energy sources are used? What is the CO<sub>2</sub> content per MWh<sub>th</sub>?**

7.7% of residential buildings use steam or hot water system heat (RECS 2015). As seen in the excerpt of *Table HC6.1* below, natural gas powers these systems in 6.6 million homes and fuel oil/kerosene in 1.7 million homes.

Main heating fuel and equipment [EIA 2015 RECS Table HC6.1]	Million housing units
<b>Natural gas</b>	<b>57.7</b>
Central warm-air furnace	46.5
Steam or hot water system	6.6
Built-in room heater	2.2
Some other equipment	2.4
Electricity	40.9
Central warm-air furnace	16.1
Heat pump	11.8
Built-in electric units	9.2
Portable electric heaters	3.0
Some other equipment	0.8
<b>Fuel oil/kerosene</b>	<b>5.8</b>
Central warm-air furnace	3.5
Steam or hot water system	1.7
Some other equipment	0.7
Propane	5.0
Central warm-air furnace	3.8
Some other equipment	1.2
Wood	3.5
Heating stove	2.7
Some other equipment	0.8
Some other fuel	Q
Do not use heating equipment	5.1

*Table 14.* Steam or hot water systems powered by natural gas or fuel oil/kerosene

- **0.86% of commercial buildings use district heat (CBECS 2012).** *Table B28, 2012 CBECS* below, shows what energy sources are used for heat networks.

Number of buildings (thousand)						
	All buildings	Buildings with space heating	Primary space-heating energy source used			
			Electricity	Natural gas	Fuel oil	District heat
All buildings	5 557	4 722	1 819	2 322	205	47
Heating equipment (more than one may apply)						
Heat pumps	628	628	484	117	Q	2
Furnaces	755	755	191	485	Q	Q
Individual space heaters	1 247	1 247	392	622	81	8
District heat	48	48	Q	Q	Q	47
Boilers	544	544	83	355	71	Q
Packaged heating units	2 802	2 802	1 057	1 506	85	3
Other	62	62	14	27	Q	Q

*Table 15.* District heating used in 0.86% of commercial buildings

### What are the main choices of the national policy – if there is one – to reduce the emissions from the existing stock of buildings? To make this reduction affordable?

There is no national policy on the reduction of emissions by buildings.

- **From a technological point of view? (Insulation, heat pumps, low CO<sub>2</sub> district network, geothermal systems, local PV production, etc.).**

There is primarily an “all of this” approach.

- **From a regulatory point of view? Through land ownership regulations?**

The United States does not have a national building code in place. Building codes are monitored and enforced at a state or municipal level and are either codes developed by private organisations (American Society of Heating, Refrigerating and Air-Conditioning Engineers and the International Code Council) or state governments.

More than half of US states currently have mandatory or voluntary energy efficiency resource standards (EERSs) in place for their electric or natural gas utilities (or both). No such standard has been adopted at the federal level.

The federal government has appliance standards in place in 60 use categories. The US Department of Energy is required to revisit the standards every six years to make updates if necessary.

- **Through subsidies, different financial mechanisms? Which are the priorities: reducing CO<sub>2</sub> or energy; Better inclusivity.**

Subsidies in the form of rebates or tax credits are the most common financial incentives.

The federal government offerings are tax credits of up to \$500 on certain appliances, and subsidies for low-income households to weatherise homes. Rebate programs also exist through state and local governments as well as utilities.

- **Replacing parts of the existing stock of buildings?**

The U.S. Green Buildings Council created and administers *Leadership in Energy and Environmental Design* (LEED) Certifications for all building types and all building phases including new construction, interior outfits, operations and maintenance and core and shell. LEED O+M (Building Operations and Maintenance) and LEED Zero (projects with net zero carbon and/or resource goals) applies to existing buildings.

- **Is there a specific roadmap for this subject?**

There is no specific roadmap for decarbonising existing buildings. The DOE Building Technologies Office (BTO) deals with most of the emission reduction efforts of buildings, including research and development at national laboratories. Incentives and requirements for buildings and their components vary by state, locality, and utility provider.

**Are there some case studies or best practices you would like to share?**

In 2016, the National Academies hosted a workshop on *Electricity Use in Rural and Islanded Communities* as part of the Quadrennial Energy Review. Curtis Wynn, Roanoke Electric Cooperative, describes therein his co-op's experience using the Rural Utilities Service (RUS) Energy Efficiency and Conservation Loan Program (RUS-EECLP) to reach their members in a more inclusive way, and how their approach benefits both members and the cooperative providing the energy. American Council for an Energy-Efficient Economy (ACEEE) covers many of the best practices for *building policies* that are currently or could be applied in the United States, as does *Resources for the Future* (RFF).

### 3.2. New buildings

**Does your country have a national policy regarding new buildings?**

**If yes, what are the priorities? (For housing and for office buildings)**

There is no specific national policy for decarbonising new buildings. Building energy codes require that a certain standard be met when building new or renovating existing buildings. However, the United States does not have a national building code in place. The existing codes are monitored and enforced at a state or municipal level, and are developed either by private organisations (American Society of Heating, Refrigerating and Air-Conditioning Engineers and the International Code Council) or state governments.

The U.S. Green Buildings Council created and administers LEED Certifications for all building types and all building phases including new construction, interior outfits, operations and maintenance and core and shell. LEED BD+C (building design and construction), ID+C (interior design and construction), ND (neighbourhood development), and Homes programs apply to new construction.

**Are some technologies prioritised? At the building level? At the infrastructure level?**

**(Developing district networks, prohibiting connection to the gas network...)**

No. The DOE Building Technologies Office (BTO) deals with most of the technology development aspects of emissions reductions in buildings. They primarily follow an "all of this" approach.

**How are they supported? Through regulations? Subsidies?**

The U.S. Department of Energy (DOE) announced on August 13, 2021 the granting of nearly \$83 million in funding to 44 projects that will lower Americans' energy bills by investing in new energy-efficient building technologies, construction practices, and the US buildings-sector workforce. All but one of these 44 projects is directly relevant to new buildings.

There are no federal regulations or incentives supporting the purchase or utilisation of lower-emitting building technologies. However, some States have such regulations (NY, CA?)

**Are there some case studies or best practices you would like to share?**

DOE has established a goal of tripling energy efficiency and demand flexibility in residential and commercial buildings by 2030, relative to 2020 levels. In May 2021, Lawrence Berkeley National Laboratory published a National Roadmap for Grid-Interactive Efficient Buildings in support of this goal.

The United States Climate Alliance, a coalition of governors committed to the Paris Climate Agreement, commissioned a Building Decarbonization Roadmap by Rocky Mountain Institute published June 2021, designed to summarise the highest-impact actions that states can take to decarbonise buildings. American Council for an Energy-Efficient Economy (ACEEE) covers many of the best practices for *building policies* that are currently or could be applied in the United States, as does *Resources for the Future* (RFF).

## 4. Industry

---

Please choose three or four industries that are important for your country:

- Steel industry (including mining),
- Cement industry,
- Chemical industry (ammonia, ethylene, plastic...).

For each of these industries:

**What is the energy balance (energy sources used)?**

**And the GHG intensity, compared to other countries?**

The U.S. EIA did its last Manufacturing Energy Consumption Survey (MECS) in 2018. Data was released across 2021, and as of August 27 is fully available. See “*Table 1.2 First Use of Energy for All Purposes (Fuel and Nonfuel), 2018*” for more details

**Steel:** 1225 trillion Btu (359 TWh) of energy were used in 2018 on Iron and Steel Mills and Ferroalloys and steel products from purchased steel, 479 (140) from natural gas, 272 (80) from coal, 238 (70) from coke and breeze, 214 (63) from electricity, 4 (1.2) from distillate fuel oil, and 18 (5) from other sources (EIA 2018 MECS). Steel is responsible for ~100 million tonnes CO<sub>2</sub> emissions (Feldmann and Kennedy, 2021). As of 2018, the carbon intensity of iron and steel production (a \$39 billion dollar industry) was 3.2 kg CO<sub>2</sub> emission per dollar value added (Broekhoff et al., 2021). As of 2020, U.S. Steel reports its North American operations’ GHG intensity to be 2.39 metric tonnes) of CO<sub>2</sub> emissions per metric tonne of raw steel produced (with 8.49 Mt raw steel produced in 2020).

**Cement:** 296 trillion Btu (87 TWh) of energy were used in 2018 on cements, 58 (17) from natural gas, 106 (31) from coal, 2 (0.6) from coke and breeze, 39 (11) from electricity, 1 (0.3) from distillate fuel oil, and 90 (26) from other sources (EIA 2018 MECS). In 2015, over 800 kg of CO<sub>2</sub> were emitted per metric tonne of cement produced (Hasanbeigi and Springer 2019). As of 2015, the carbon intensity of cement production (a \$5 billion dollar industry) is 15.1 kg CO<sub>2</sub> emissions per dollar value added (Broekhoff et al., 2021).

**Chemical:** 7724 trillion Btu (2263 TWh) of energy were used in 2018 on chemicals (subcategories in below table). 3234 trillion Btu (948 TWh) were from natural gas, 2839 (832) from Hydrocarbon Gas Liquids (HGL), 130 (38) from coal, 2 (0.6) from coke and breeze, 501 (147) from electricity, 9 (2.6) from distillate fuel oil, 45 (13) from residual fuel oil, and 965 (283) from other sources (EIA 2018 MECS). As of 2018, the carbon intensity of cement production (a \$256 billion dollar industry) is 1 kg CO<sub>2</sub>e per dollar value added (Broekhoff et al., 2021). See <https://www.epa.gov/ghgreporting/ghgrp-chemicals-for-2019-data-on-chemical-emissions>.

Sub-sector and Industry	Total (b)	Net Electricity (c)	Residual Fuel Oil	Distillate Fuel Oil (d)	Natural Gas (e)	HGL (excluding natural gasoline) (f)	Coal	Coke and Breeze	Other (g)	Shipments of Energy Sources Produced Onsite(h)
Chemicals	7 141	501	45	9	3 234	2 839	130	2	965	583
Petrochemicals	1 461	24	0	1	307	1 204	0	0	347	422
Industrial Gases	291	74	0	*	243	*	0	0	4	30
Other Basic Inorganic Chemicals	555	101	44	*	264	55	33	2	57	0
Ethyl Alcohol	453	37	0	*	360	*	44	0	12	0
Cyclic Crudes, Intermediate and Gum and Wood Chemicals	233	11	0	*	120	78	3	0	30	9
Other Basic Organic Chemicals	1 366	65	*	Q	597	412	42	0	333	88
Plastics Materials and Resins	1 675	58	0	D	458	D	D	0	D	34
Synthetic Rubber	38	5	0	*	19	3	2	0	9	0
Artificial and Synthetic Fibres and Filaments	33	9	0	*	23	*	*	0	*	0
Nitrogenous Fertilisers	614	18	0	*	D	*	0	0	D	0
Phosphatic Fertilisers	37	D	*	D	29	*	D	0	*	0

**Table 16.** Energy consumption in the chemical industry by product and by fuel type in trillion Btu  
(1 trillion Btu = 0,293 TWh)

## Are the best available low carbon technologies used/considered?

### If not, is it an economic problem? A matter of regulation? Or some social issues?

**Steel:** In many cases, yes. 70% of American steel is produced by recycling steel scrap to produce new steel using electric arc furnace (EAF). Steel produced by blast furnace and basic oxygen furnace (BF/BOF) technology in the United States has the lowest CO<sub>2</sub> intensity of steel produced via BF/BOF in the seven largest steel producing countries. BF/BOF steel production is fed almost entirely by domestically sourced iron ore pellets, resulting in lower emissions of CO<sub>2</sub>, as well as NO<sub>x</sub>, SO<sub>2</sub> and particulate matter (Mourao et al., 2020). The steel industry is also pursuing R&D in increased use of renewable energy in steel production, and advancements in domestic production using direct reduced iron (DRI) and hot briquetted iron (HBI) in place of pig iron in both integrated and EAF steelmaking. HBI and DRI use natural gas as a reductant which will further increase blast furnace and electric arc furnace productivity and reduce CO<sub>2</sub> emissions. The American steel industry uses a higher percentage of low-emitting natural gas than most other countries. Boston Metal process emissions.

**Cement:** In most cases, no. US cement production has, on average, the highest electricity intensity, fuel intensity, and carbon intensity (15.1 kg/\$ value added [Broekhoff et al., 2021]) in the world. This is in part due to the high clinker-to-cement ratios used in US cement plants, partially because blending with Supplementary cementing materials (SCMs) typically occurs at concrete mixing plants after the cement is produced, but also due to plant ages, types of cement produced, and fineness of clinker grinding.

**Chemical:** Low carbon technologies are used in some chemical production, not often for their lower emissions but rather for economic reasons, where they intersect with increased production volumes or greater production efficiencies.

## Is there a roadmap to decrease GHG emissions for 2030 - 2050

### If yes, what are the intermediary steps?

No, there is no national roadmap for industrial emissions. The Portland **Cement** Association and U.S. **Steel** have both published roadmaps to carbon neutrality by 2050.

### Is the implementation of low-carbon technologies helped by the government? For refurbishing or replacing equipment? How are public authorities pushing the transformation? Through benchmarking? Audits?

Low-carbon industrial technologies are mainly supported by the federal government through the funding of RD&D, mostly through ARPA-E and DOE.

**Steel:** The U.S. Department of Energy has provided significant funding to support Boston Metal's MOE process (see section 3.7 for more detail on this steelmaking process).

### Are there incentives for carbon capture, utilisation, and storage? How?

The U.S. Department of Energy is actively researching and investing in carbon capture, utilisation, and storage technologies, with most research conducted at the National Energy Technology Laboratory (NETL). The National Academies have released multiple reports on this topic in recent years, including *Negative Emissions Technologies and Reliable Sequestration* and *Gaseous Carbon Waste Streams Utilization*. In December 2019, U.S. House and Senate appropriators provided \$60 million, the first dedicated funding for carbon removal technology development.

For existing CCUS technologies, the Code Section 45Q tax credit is the main incentive, enacted in February 2018, industrial manufacturers that capture carbon from their operations can earn \$50 per metric tonne of CO<sub>2</sub> stored permanently or \$35 if the CO<sub>2</sub> is put to use, such as for enhanced oil recovery (EOR). There are no specific incentives for the **steel**, **cement**, and **chemical industries** in the United States to pursue CCUS technologies.

### If relevant, what about recycling? What percentage is recycled? What are the obstacles to increase recycling? Is a policy to increase recycling already in place or in project?

**Steel:** There are typically 60 to 80 million tonnes of steel scrap recycled per year into new steel products. Steel is the most recycled product in the US, and 100% of the co-products of the steel production process can be beneficially used.

**Cement:** The Construction Materials Recycling Association estimates that about 140 million tonnes of concrete are recycled each year in the United States. Concrete products can be crushed and used as aggregate for new Portland cement concrete products, usually mixed with virgin aggregate or used in sub-base layers. This saves energy in mining, processing, and transporting new aggregates, as well as landfill avoidance, which is important due to the high volume of concrete removed from demolition sites.

### Are there some case studies or best practices you would like to share?

**Steel:** Boston Metal is pursuing an alternative steel production method called molten oxide electrolysis (MOE), which requires inputs of iron ore and electricity. This process is more energy efficient, using 4 MWh of electricity to produce one tonne of crude steel, rather than 5.5 MWh of coal in traditional steel production. This results in significantly lower emissions, as long as there is sufficient low-carbon electricity.

## References

- American Iron and Steel Institute. 2021. "Sustainability of the American Steel Industry." March. Accessed September 9, 2021. <https://www.steel.org/wp-content/uploads/2021/03/Sustainability-Key-Messages.pdf>.
- Broekhoff, D., S. Ulloa, and J. Veysey. 2021. "To Decarbonize U.S. Industry, Look to Federal and State-Level Partnerships - Leadership Group for Industry Transition." Leadership Group for Industry Transition (LeadIT). May 24. <https://www.industrytransition.org/insights/decarbonize-us-industry-federal-state-level-partnerships/>
- Cleary, K., and K. Palmer. 2021. "Federal Climate Policy 106: The Buildings Sector." Resources, April 6. Accessed September 9, 2021. <https://www.rff.org/publications/explainers/federal-climate-policy-106-the-buildings-sector/>
- Feldmann, J., and K. Kennedy. 2021. "Toward a Tradable, Low-Carbon Product Standard for Steel: Policy Design Considerations for the United States," March. <https://www.wri.org/research/toward-tradable-low-carbon-product-standard-steel-policy-design-considerations-united>
- Hasanbeigi, A. and Springer, C. 2019. California's Cement Industry: Failing the Climate Challenge. Global Efficiency Intelligence, San Francisco, CA. <https://www.climateworks.org/report/californias-cement-industry-failing-the-climate-challenge/>
- Mourao, J., I. Cameron, M. Huerta, N. Patel, and R. Pereira. 2020. Comparison of sinter and pellet usage in an integrated steel plant 1. [https://www.researchgate.net/publication/341386739\\_comparison\\_of\\_sinter\\_and\\_pellet\\_usage\\_in\\_an\\_integrated\\_steel\\_plant\\_1](https://www.researchgate.net/publication/341386739_comparison_of_sinter_and_pellet_usage_in_an_integrated_steel_plant_1)

## 5. Case study

### Localizing Climate Solutions: Case Study of Drawdown Georgia

Dr. Marilyn A. Brown (mbrown9@gatech.edu)

Professor of Sustainable Systems, School of Public Policy, Georgia Institute of Technology

Avoiding costly climate change necessitates actions at every political scale and across all sectors of the economy. Drawdown Georgia illustrates how robust place-specific plans for climate action can be derived from foundational global and national work and by embedding that research into the context of socio-ecological-technological systems. Its replicable methodology advances the science of carbon abatement by incorporating solution interdependencies, by spanning both carbon sources and sinks, and by emphasizing beyond-carbon societal costs and benefits including their distributional impacts. By focusing on the 2030 timeframe, Drawdown Georgia highlights pathways for immediate action that can help put sub-national jurisdictions onto a path toward net-zero emissions by mid-century. However, it recognizes that post-2030, additional solutions will likely be cost-effective and necessary for deeper reductions.

### Down-Selection of 20 Solutions

Engaging universities and stakeholders across the state, 20 high-impact solutions for Georgia were identified, spanning five sectors. They address a combination of traditional sources of carbon emissions from electricity generation, transportation, and the energy consumption of buildings. In addition, they tackle emissions from agriculture and food systems, and they focus on the carbon absorbed in trees and soils. These solutions are diverse, and many of them depend on the actions of consumers—such as rooftop solar, electric vehicles, recycling, plant-rich diets, and composting organic waste. Others depend on the actions of businesses and industry, such as refrigerant management, conservation agriculture, increasing forest cover, and generating electricity from landfill methane. Some depend on significant public funding, such as mass transit, and they all would benefit from private investments and supportive public policies.

Approximately 100 climate solutions were examined by applying a sequence of filters covering applicability to Georgia, technology readiness, magnitude of impact, cost-effectiveness and beyond-carbon attributes. *Figure 14* presents the carbon abatement cost curve that aligns costs and benefits with megatons of carbon reduction for the final set of 20 high-impact climate solutions. Per megaton of abatement, the solutions range from net savings of \$336 to net costs of \$144. The estimated total financial impact of achieving a 35% reduction of CO<sub>2</sub>-e in 2030 ranges from net benefits of \$1.3 billion to net costs of \$148 million.

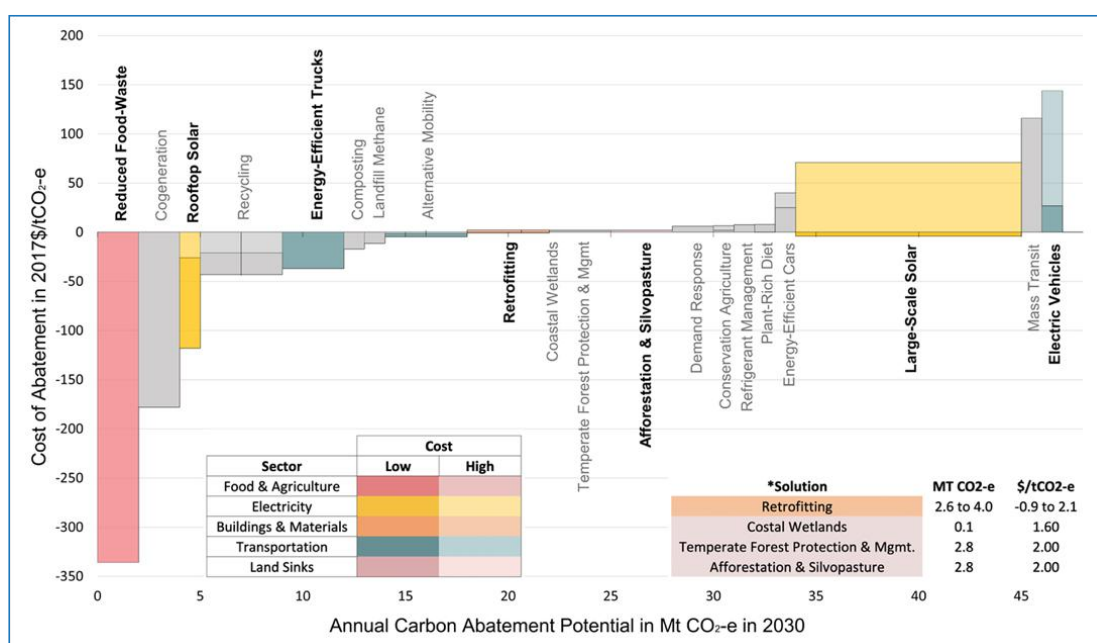


Fig. 14. Carbon Cost Abatement Curve

(Note: Abatement costs and potentials have ranges for some solution, that are highlighted by dividing boxes vertically and horizontally.)

On the left side of the abatement cost curve are the solutions that deliver the largest net benefits (reduced food waste, rooftop solar, and cogeneration). Consumers and businesses can make money by investing in them. For example, companies in many industries can cut their energy bills by buying their own generation equipment and running it primarily on waste heat. On the right side are the solutions that deliver the highest net costs (electric vehicles and mass transit, in particular). Mass transit requires significant public investments, but based on the array of key benefits, the expenditures are justifiable.

Figure 15 aligns these 20 solutions with a multi-criteria assessment of societal attributes to acknowledge the hard-to-monetize costs and benefits of each solution and to consider equity as it relates to their distribution.

Legend		Environment					Equity					Economic Development & Jobs							Public Health				
	Largely Positive (+1)	Air Quality	Water Quality & Quantity	Land Use	Ecosystem & Biodiversity	Material Disposability	Affordability	Workforce & Business Diversity	Public Health Impacts	Accessibility of Solutions	Cultural Fit & Way of Life	Local Economy & Employment	Input Prices & System Costs	Workforce Job Quality (i.e. skilled)	Wages and Benefits	Property Values/Tax	Infrastructure Requirements	Premature Mortality	Morbidity	Quality of Life	Education	Public Safety	
	Mixed/Need Attention (-1)																						
	Limited Impact or Data																						
1. Reduced Food Waste																							
2. Cogeneration																							
3. Rooftop Solar																							
4. Recycling																							
5. Energy-Efficient Trucks																							
6. Composting																							
7. Landfill Methane																							
8. Alternative Mobility																							
9. Retrofitting																							
10. Coastal Wetlands																							
11. Temperate Forest Protection & Mgmt.																							
12. Afforestation & Silvopasture																							
13. Demand Response																							
14. Conservation Agriculture																							
15. Plant Rich Diet																							
16. Energy-Efficient Cars																							
17. Refrigerant Management																							
18. Large-Scale Solar																							
19. Mass Transit																							
20. Electric Vehicles																							

Fig. 15. Multi-Criteria Assessment of Selected Attributes

By comparing the baseline forecast and achievable scenarios for each of the 20 high-impact solutions, we estimated their potential to contribute to carbon abatement in 2030. Summing the results over the decade produces the “wedge” diagrams shown in Figure 16. The grey band across the top shows carbon sinks at about 46 megatons, Georgia’s current carbon footprint of about 122 megatons, which is also the baseline forecast for 2030. The colored wedges below the gray band represent the carbon abatement associated with each of the 20 solutions, showing how much each solution could contribute over the next decade, by year from left to right. For example, the largest wedge represents utility-scale solar that increases from 3.9 megatons in 2021 to 11.2 megatons in 2030. The wedge for energy-efficient trucks grows from 0.5 megatons in 2021 to 3.3 megatons in 2030. When all 20 abatement estimates are included and two major interactions are taken into account, the projected total GHG emissions in 2030 would fall from the forecast of 122 megatons to 79 megatons, a 35% reduction. Relative to Georgia’s 156.5 megatons of net emissions in 2005, this would be a 50% reduction, which is consistent with the 2015 Paris Climate Agreement.

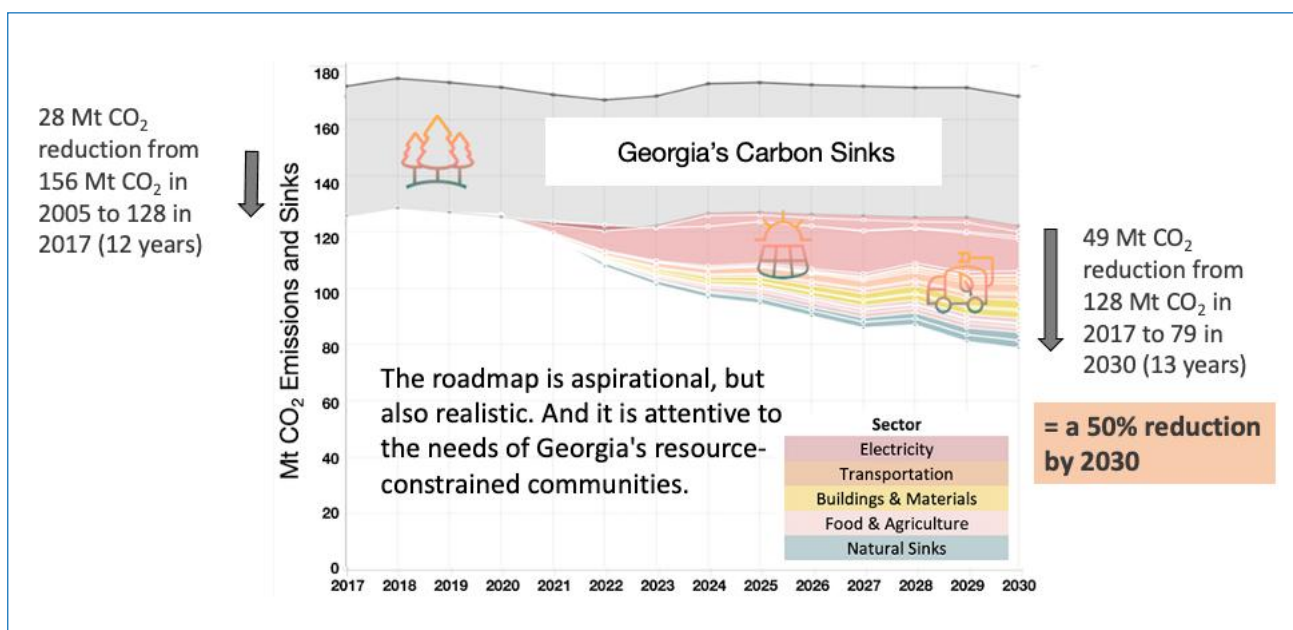


Fig. 16. The Achievable Abatement Potential of 20 High-Impact Solutions for Georgia

In sum, putting all the parts together, we show that this scenario of 20 solutions could reduce Georgia's carbon footprint at no net financial cost. However, implementing some solutions will require public support through information/outreach and technical assistance programs, while others will require direct financial outlays from private individuals/firms or public institutions. This conclusion is independent of the co-costs (such as the handling of hazardous waste streams) and co-benefits (such as improved public health and coastal land storm protection) that can result from implementing these solutions.

Next steps for Drawdown Georgia include the creation of a dashboard to monitor monthly GHG emissions by county and metro area in the state of Georgia. In addition, nearly 20 Georgia companies operating in Georgia have signed the Georgia Climate Compact and the Drawdown Georgia team will be working with them to build a community-of-interest. Finally, we have created a Climate Solutions Game and we are in the process of evaluating the results of a public survey to ascertain the attitudes of state residents to climate solutions and policies, which will provide key inputs to climate action planning across Georgia.

Learn more about Drawdown Georgia Research here: <https://doi.org/10.1073/pnas.2100008118> and <https://cepl.gatech.edu/projects/Drawdown-Georgia>

Learn more about the Drawdown Georgia Project here: [Drawdownga.org](http://Drawdownga.org)

---

# SECTOR ANALYSIS QUESTIONNAIRES

Table of Contents

Nigeria ..... 458

## Nigeria

### What is the energy balance (energy sources used)?

#### And the GHG intensity, compared to other countries?

Nigeria is endowed with abundant natural energy resources including fossil and renewable reserves. The country is energy-rich and ranks as the 11<sup>th</sup> largest global producer of oil<sup>1</sup> (about 2 million barrels/day) and the 9<sup>th</sup> biggest gas producer accounting for 3% of the world's total natural gas reserves (6 923 trillion cubic feet)<sup>2</sup>. Fossil energy (oil, gas and coal) was about 97% of the total production (5.93 quads - 1738 TWh) in 2018 with renewables (hydro-power, wind, solar and biofuels) accounting for the balance<sup>3</sup>. Indeed, oil and gas contribute about 86% of the nation's total export earnings. Nigeria's strong reliance on fossil fuels to power its economy is also reflected in the energy consumption<sup>4</sup> history during the last three decades as shown in *Fig. 1*. The rapid rise in natural gas consumption reflects the preponderance of gas-powered plants for electricity generation, especially since the turn of the 21<sup>st</sup> century. Through its Natural Gas Expansion Programme (NGEP), the government is implementing gas utilisation and expansion activities. However, despite the diversity of renewable energy resources<sup>5</sup>, its relatively flat profile is indicative of weak government efforts at promoting national uptake in this energy category. Crucially, the agricultural sector in Nigeria has access to less than 1% of the total energy supply in the country<sup>6</sup>. This is worrisome, given that the country consumed about 1.655 quads (485 TWh), for example, in 2018 and is presently driving a strong agricultural mechanisation and processing agenda.

Greenhouse gases (GHGs) released during energy-related activities typically contribute to global warming. The emissions intensity (release rate of the emitted gases relative to a specific activity or an industrial production process such as the quantity of energy produced or the GDP) may therefore be used as an environmental impact metric. GHGs include CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, SF<sub>6</sub>, PFCs, HFCs and others as listed comprehensively in the IPCC Report<sup>7</sup>. *Fig. 2* illustrates the CO<sub>2</sub> intensity profiles for representative nations from Europe, the Americas, Asia, Africa and Oceania. CO<sub>2</sub> was used as a proxy for total GHGs data as obtained from the World Bank<sup>8</sup>. The CO<sub>2</sub> intensity for Nigeria appears to have generally decreased from 1.19 to 0.67 (kg CO<sub>2</sub> released/kg oil equivalent energy use) over the past three decades. Whilst this is a desirable trend from an environmental perspective, the underlying interplay of factors may, however, be more complex than appears on the surface of these data. Even so, South Africa, the largest economy on the African continent seemed to be in a poorer position with a CO<sub>2</sub> intensity exhibiting a general rise from 2.55 to 3.05 within the same period – an unenviable trajectory. Nigeria is, in fact, second to South Africa as the largest GHG emitter on the continent but 17<sup>th</sup> on the global ladder. More detailed analyses and in-depth comparisons with other nations are beyond the scope of this feedback.

<sup>1</sup> <https://www.investopedia.com/articles/investing/101515/biggest-oil-producers-africa.asp>

<sup>2</sup> <https://www.worldometers.info/gas/nigeria-natural-gas/#:~:text=Gas%20Reserves%20in%20Nigeria&text=Nigeria%20holds%20187%20trillion%20cubic,306.3%20times%20its%20annual%20consumption.>

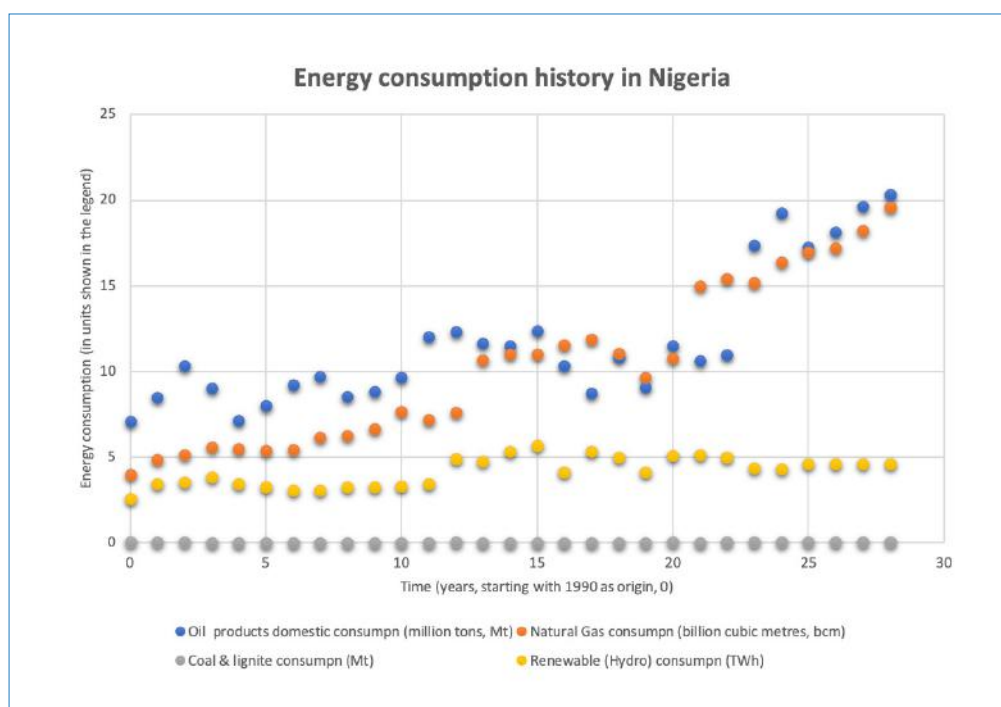
<sup>3</sup> <https://www.eia.gov/international/data/country/NGA/>

<sup>4</sup> [World Energy Statistics | Enerdata](#)

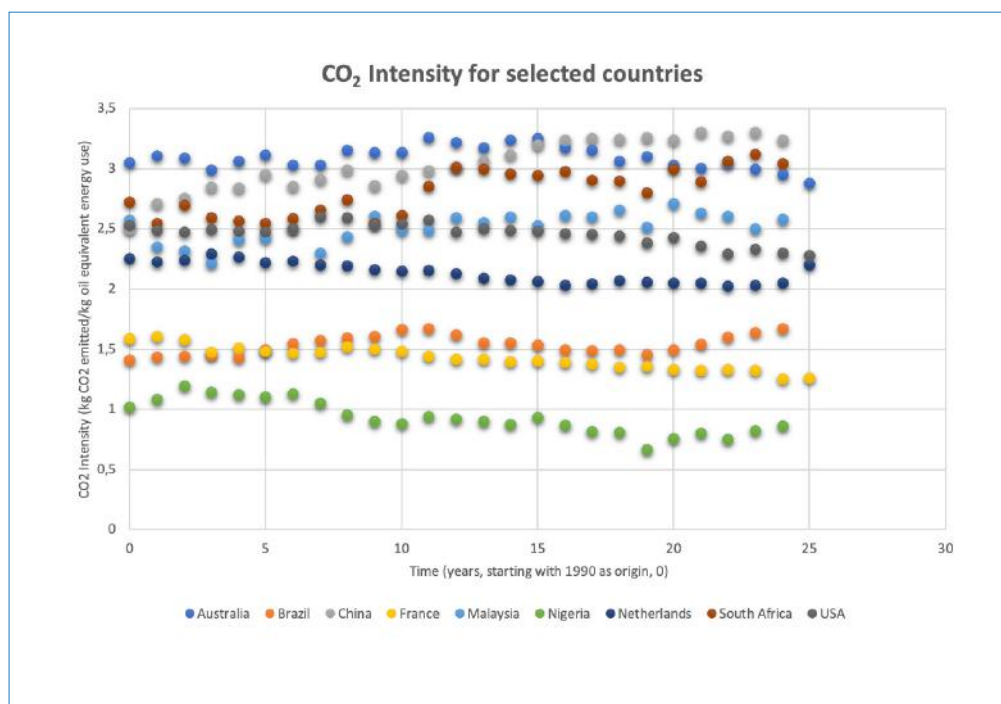
<sup>5</sup> <https://www.iea.org/policies/4974-nigeria-renewable-energy-master-plan>

<sup>6</sup> Onyema M-A. C., (2016), International Food Policy Research Institute: Nigeria Strategy Support Program, Policy Note No. 24.

<sup>8</sup> <https://data.worldbank.org/conc>



**Fig. 1.** Nigeria's energy consumption profile between 1990-2020.



**Fig. 2.** CO<sub>2</sub> intensity history over the last three decades

### Are the best available low-carbon technologies used/considered?

If not, is it an economic problem? A matter of regulation? Or some other social issues?

The Federal Government of Nigeria (FGN) produced a Vision 2020 document which identified Agriculture & Land as one of the four areas (i.e. agriculture & land use; oil & gas; power; transport) where the application of low-carbon technologies may help in realising the vision to become the 20<sup>th</sup> largest global economy. However, an examination of the publicly accessible documents on the website of the Federal Ministry of Agriculture and

Rural Development<sup>9</sup> (FMARD) revealed that there seems to be no policy framework to stimulate economic growth in key carbon-emitting sectors that can lead to a reduced carbon footprint. This means that GHG emissions would increase over the next decade or at best, be maintained at their present value (ca. 0.67 tonnes CO<sub>2</sub> per capita). Additionally, the unavailability of low-carbon technologies may be attributed to poor political commitment as evidenced by the absence of an appropriate regulatory agency. Nonetheless, there is a consistent growth within the private sector, of investment activities in renewable energy (solar-powered farms, water supply, etc) and carbon reduction (gas-powered automobile/transportation) technologies.

## Is there a roadmap to decrease GHG emissions for 2030 or 2050?

### If yes, what are the intermediary steps?

The Nigerian government has committed to reducing its GHG emissions by 20% by 2030 when compared to the “business-as-usual” practice but has opened the window for a possibility of a reduction by up to 45% if it has international support<sup>10</sup>. It is estimated that Nigeria’s nationally-determined contribution (NDC)<sup>11, 12</sup> to GHG emissions by 2030 will be about 453 million tonnes of CO<sub>2</sub> equivalent – a 31% increase from its 2018 level – if there is no mitigation effort. The country is especially vulnerable to climate change impact because of its tropical location and the dependency of the agricultural sector on a reliable rain-fed pattern. The government’s National Climate Change Policy (2021-2030)<sup>13, 14</sup> is a new roadmap for the reduction of emissions en route to 2030. The country is also benefitting from the \$10.6 billion UN initiative on Reducing Emissions from Deforestation and Forest Degradation programme (REDD+) via the new national REDD+ Strategy (2021)<sup>15, 16</sup> on land use and forestry, to the tune of \$7.6 million.

The Agricultural Promotion Policy (APP) of the present FMARD has led to the “Green Alternative” document<sup>17</sup>. Although the new policy highlights eleven national priorities, only one of them, “Factoring climate change and environmental sustainability” carries the explicit notion that the policy instrument may engage low-carbon technologies to mitigate GHG emissions as well as land, soil and natural ecosystems for improved agricultural sector productivity. In fact, in 2018, the Agriculture, Forestry and Other Land Use (AFOLU) sector contributed the country’s 2<sup>nd</sup> largest (25%) GHG emissions<sup>11</sup> (with the energy sector being the 1<sup>st</sup> with 60% contribution i.e. 209 million tonnes of CO<sub>2</sub> equivalent). However, under Business-as-Usual conditions, the energy and agricultural sectors will contribute 51% and 33% respectively by 2030 to the national GHG emissions. Interestingly, existing renewable energy sources for agricultural production and processing activities, especially in rural areas, are being harnessed (and necessitate promotion) as Sambo<sup>18</sup> has summarised (cf. *Table 1.*).

Energy Source	Reserves	Energy Capacity
Crop residue	83 million tons/year	5.3 × 10 <sup>11</sup> MJ (147.2 TWh)
Animal waste	227.5 tons per day	2.2 × 10 <sup>9</sup> MJ (0.611 TWh)
Saw dust	1.8 millions/year	31.43 × 10 <sup>6</sup> MJ (0.009 TWh)
Fuel wood	80 million m <sup>3</sup> /year	6.0 × 10 <sup>9</sup> MJ (1,667 TWh)
Biogas	6.8 million m <sup>3</sup> /day	199.24 TJ (0.055 TWh)
Solar	6.25 hours/day	6.25-7.0 kWh/m <sup>2</sup> daily
Wind	2-4 m/s at 10 m height	5 MW
Small hydropower	0.143 billion tons (of water)	734.2 MW

**Table 1.** Potential sources of energy for rural agricultural production and processing in Nigeria

<sup>9</sup> <https://fmard.gov.ng/green-alternative/>

<sup>10</sup> Party (unfccc.int) ; UNFCCC

<sup>11</sup> <https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Nigeria%20First/NDC%20INTERIM%20REPORT%20SUBMISSION%20-%20NIGERIA.pdf>

<sup>12</sup> <https://www.ndcs.undp.org/content/ndc-support-programme/en/home/our-work/geographic/africa/Nigeria.html>

<sup>13</sup> <https://climatechange.gov.ng/wp-content/uploads/2020/09/national-climate-change-policy-1-1.pdf>

<sup>14</sup> <https://climate-laws.org/geographies/nigeria/policies/national-policy-on-climate-change-67399bf5-f1f8-4102-9a15-5fa7e597a551>

<sup>15</sup> <https://www.un-redd.org/post/2018/06/21/community-based-redd-programme-in-nigeria-a-success-story>

<sup>16</sup> <https://republic.com.ng/april-may-2020/redd-in-nigerias-last-rainforests/>

<sup>17</sup> <https://agra.org/wp-content/uploads/2017/12/agra-nigeria-final.pdf>

<sup>18</sup> Sambo, A. S. (2005). “Renewable energy for rural development. The Nigerian perspective”. *UNESCO: Science and Technology Vision 1: 12-22.*

## Is the implementation of low-carbon technologies helped by the government?

**For refurbishing or replacing equipment? How are public authorities pushing this transformation? Through benchmarking? Audits?**

As a signatory to the Paris Agreement, Nigeria's pledge to roll out solar power technologies and end gas flaring seems to be working (a reduction in gas flaring by 70% between 2000 to 2019), albeit slowly. Developments in agricultural mechanisation are being spear-headed by nearly 40 government agencies involved with various food and agricultural technologies such as National Agency for Science & Engineering Infrastructure (NASENI) and National Centre for Agricultural Mechanisation (NCAM). For example, NASENI, through collaboration with state governments, deploys agricultural innovations promoting decarbonisation<sup>19</sup>. While government efforts in the implementation of the Agricultural Transformation Agenda (ATA) have been largely fruitful, international benchmarking activities are somewhat diffuse. It is evident that public authorities and recent policies are lethargic in pushing low carbon economic transformation. This could be seen in the Petroleum Industry Act (PIA 2021) which places emphasis on increased prospecting of fossil fuels rather than on renewable energy investments in frontier locations and on the lack of targeted emphasis in the Economic Recovery & Growth Plan (2017-2020)<sup>20</sup>.

## Are there incentives for carbon capture, utilisation and storage? How?

The importance of carbon capture, storage and utilisation (CCSU) technologies in the decarbonisation of the Nigerian economy has been discussed in several papers<sup>21, 22, 23</sup>. These studies placed a premium on the realisation of the FGN's Vision 2020, especially regarding the 6-fold improvement in domestic agricultural production while offering a basis (through different scenario analyses) for government policy formulation and implementation. The absence of incentives for adopting CCS technologies (even in the more recent APP) by small-scale farmers and government-owned agricultural plantations is rather bewildering.

## If relevant, what about recycling?

The recycling programme is under the auspices of the Federal Ministry of Environment, embedded in the department's Clean & Green Initiative. In practice, however, solid waste management (collection, processing and recycling) is often a state affair (there are 36 states in Nigeria). Lagos State, where Africa's largest city, Lagos, is located, runs an enviable recycling programme under the agency of the Lagos State Waste Management Authority. The programme has become a model for other big cities such as Ibadan, Abuja, Kano and Port-Harcourt. The LAWMA recycle programme is decentralised to the 57 local government areas (LGAs) in the state where private recycling companies handle the waste collection, processing and materials recovery. Over 40 million tonnes of waste are produced annually in Nigeria with about 30% of this as recyclable plastics, electronic wastes and other PVC materials. The recycling business is principally organised by the informal sector through social participation (waste pickers subcontracted by private companies). Thus, the absence of a central policy on solid waste management has led to a proliferation of private recycling companies operating with little or no regulation<sup>24</sup>. Despite the central government's relative apathy towards recycling, private Nigerians have developed a niche market for waste-to-wealth technologies as exemplified by young entrepreneurs like Victor Boyle-Komolafe whose company, GIVO, is processing plastic bottles into plastic face shields<sup>25</sup>. By the same token, a partnership between Nigeria's National Environmental Standards & Regulation Enforcement Agency, the UN Environment Programme, and a private company, Global Environment Facility, has led to Nigeria's first e-waste processing facility<sup>26</sup>. Other developments are found in public institutions where recycling and waste valorisation activities provide a parallel revenue stream in the overall waste management arm. With its

<sup>19</sup> <https://naseni.org/>

<sup>20</sup> [https://www.cbn.gov.ng/Out/2017/CCD/Financial%20Inclusion%20Newsletter\\_%20MAY%202017\\_Volume%202%20Issue%20-final%20-%20Review%20%20%20.pdf](https://www.cbn.gov.ng/Out/2017/CCD/Financial%20Inclusion%20Newsletter_%20MAY%202017_Volume%202%20Issue%20-final%20-%20Review%20%20%20.pdf)

<sup>21</sup> Cervigini R., Dvorak I. & Rogers J.A. (2013), "Assessing low-carbon development in Nigeria: An analysis of four sectors." World Bank Series. <https://openknowledge.worldbank.org/handle/10986/15797>

<sup>22</sup> Galadima A. & Garba Z. (2008), "Carbon capture and storage (CCS) in Nigeria: Fundamental science and potential implementation risks." Sci. World J. 3(2), 95-99.

<sup>23</sup> Ugwuishiwu B.O., Nwakaire J.N. & Ohagwu C.J. (2019), "Cost analysis of carbon capture and storage for current gas-fired power plants in Nigeria." Greenhouse Gases: Science and Technology, 9(2), 370-386.

<sup>24</sup> Nzeadibi T.C. & Adama O. (2013), "Improved recycling performance: Policy options for Nigerian cities", The Nordic Africa Institute, Policy Note 2.

<sup>25</sup> <https://www.government.nl/latest/news/2021/04/08/%E2%80%98over-the-next-five-years-we%E2%80%99re-going-to-recycle-150-million-plastic-bottles%E2%80%99>

<sup>26</sup> <https://www.unep.org/news-and-stories/press-release/nigeria-turns-tide-electronic-waste>

burgeoning population, continuing advocacy with the Federal government on a robust policy for education on recycling is essential to avoid a degenerative or even chaotic market environment.

**Are there some case studies or best practices you would like to share?**

In terms of smart technology embrace, development and business practices, the Lagos State Waste Management Authority provides inspiration for the future of sustainable resource harnessing in Nigeria. LAWMA<sup>27</sup> has received both national and international awards for its adventures.

---

<sup>27</sup> <https://www.lawma.gov.ng/index.html>

Table of Contents

China

.....

464

Croatia

.....

468

Sweden

.....

471

Uruguay

.....

476

## China

### Existing and new buildings

#### Energy balance 2019 (energy sources to end-uses)

Based on our long-term research on the energy consumption of civil building operations, considering the difference in the heating method in winter, the difference in lifestyle and types of buildings of urban and rural areas and the difference in activities and devices that consume energy in Northern China and Southern China, building energy use could be divided into four categories: **northern urban heating (NUH)**, public and P&C buildings (excluding NUH), urban residential buildings (excluding NUH) and rural residential buildings as described below.

#### Systems used for heating

##### Energy use for NUH

Refers to the energy use of various provinces, autonomous regions and municipalities such as all urban areas in Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia autonomous regions, Liaoning, Jilin, Heilongjiang, Shandong, Henan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang autonomous region and part of Sichuan province that use district heating methods in winter. Heating is also needed for the cold winter in the Tibetan autonomous region, Western Sichuan and part of Guizhou provinces. However, the situations in Tibet, Western Sichuan and Guizhou are quite unique and thus should be treated independently. The reason for taking NUH energy use as an independent category is that district heating has been the main heating method in northern urban areas. This is the area where we would see many heat-supply networks in cities and communities. Different from other types of energy use in buildings, where the calculation is based on the consumption of single buildings or single households, the energy use for NUH depends mainly on the structure and the operation mode of the heating system, and the calculation of the energy used for heating in northern urban areas is based on the heating system as a whole, which is why we regard the energy use of this area as an independent category. Based on heat sources and the scale of heating, centralised heating methods include large- and mid-scale combined heat and power generation (CHP), small-scale CHP, district coal-fired boilers, district gas-fired boilers, community-level coal-fired boilers, community-level gas-fired boilers, and centralised heat pumps. Decentralised heating methods include household gas furnaces, household coal furnaces, air conditioners and direct electrical heating. The energy use considered in this report includes the primary energy consumption at the heat source and the power use of various related equipment (fan, water pump). Energy consumption can also be divided into transitional heat loss from heat sources and heating stations, heat loss from pipelines and transmission processes, and heat gain for buildings.

##### Urban residential building energy use (excluding NUH)

This refers to residential building energy use in urban areas excluding NUH. It includes energy use for household appliances, air conditioners, lighting, cooking, domestic hot water (DHW), and winter heating of the hot summer and cold winter (HSCW) climate zone. The energy types mainly include electricity, coal, natural gas, liquefied petroleum gas, etc. The main winter heating method in HSCW areas was decentralised, and the heat source included an air source heat pump, direct electrical heating, and local heating methods such as coal-fired stoves, electrical heating blankets, and electrical hand warmers.

##### Public and commercial building energy use (excluding NUH)

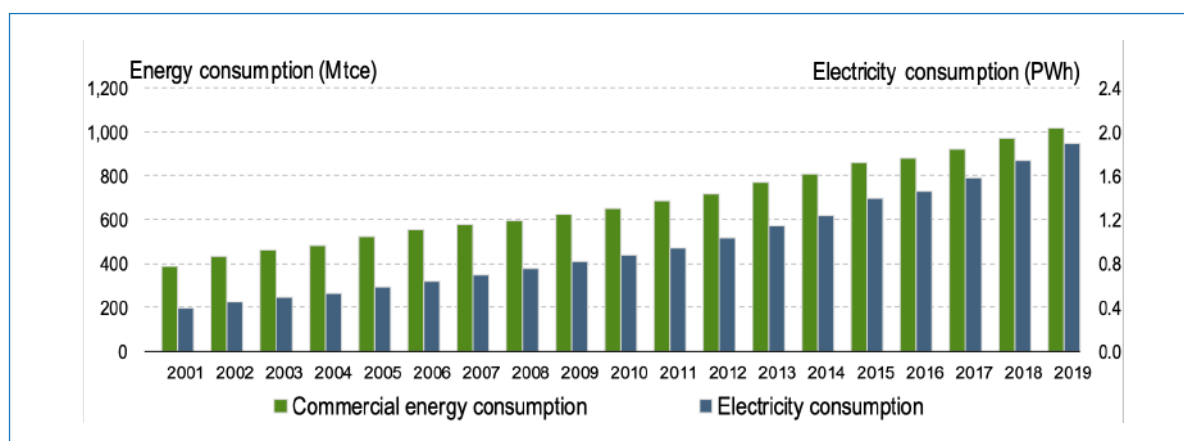
Refers to buildings for public and commercial purposes, including offices, commercial buildings, tourism buildings, buildings for educational purposes, buildings for communication and buildings for transportation in urban and rural areas. Apart from NUH energy use, the energy use of P&C buildings includes air conditioning, lighting, electricity sockets, elevators, cooking, and winter heating in the HSCW zone. Electricity, natural gas, oil and coal are the main energy sources for P&C buildings.

##### Rural residential buildings' energy use

This refers to the energy consumed by rural households, including cooking, heating, cooling, lighting, domestic hot water, household appliances, etc. Electricity, coal, LPG, natural gas and biomass energy (straw burning,

firewood) are the major energy sources. Biomass was not included in national energy statistics, but it will be an independent category in this report.

The data of this report came from the China Building Energy Model (CBEM) from BERC, Tsinghua University, which delineated the status quo of China's building energy consumption and its transformation between 2001 and 2019. From 2001 to 2019, the sum total building energy use increased dramatically, as shown in *Figure 1*. In 2019, the total commercial energy use during the building operation stage amounted to 1.02 Gtce (8 304 TWh), accounting for 22% of the national energy consumption. The energy use of all building-related products and biomass was 1.11 Gtce (9 036 TWh) (0.09 Gtce (733 TWh) of biomass), and detailed information is presented in *Table 1*.



*Fig. 1.* Primary energy consumption and total electricity use for building operation in China (2001~2019) – 1Mtce = 8,14 TWh

Types of energy	Activity data (Floor space or number of households)	Electricity (TWh)	Commercial energy (Mtce)	Primary energy use intensity
NUH	15.2b m <sup>2</sup>	61.1	213	14.1kgce/m <sup>2</sup> (115 kWh/m <sup>2</sup> )
UR buildings (Excluding NUH)	28.2b m <sup>2</sup>	537.4	242	792kgce/h (6 447 kWh/hh) h
P&C buildings (Excluding NUH)	13.4b m <sup>2</sup>	993.2	342	25.6kgce/m <sup>2</sup> (208 kWh/m <sup>2</sup> )
RR buildings	22.8b m <sup>2</sup>	305.4	222	1 527kgce/hh (12 431 kWh/hh)
Total	1.4b people 64.4b m <sup>2</sup>	1 897.2	1 020	

*Table 1.* China energy use in buildings (2019) – b = billion, hh = household, ce = coal equivalent

The sum of the energy consumption and intensity of the four building types can be found in *Figure 2*, in which the building floor area is represented by the horizontal axis and the energy intensity per square meter is represented by the vertical axis. The size of the square refers to the total energy use of the building. From the aspect of building stock, urban residential and rural residential were the biggest, and building stock within the NUH accounted for one-fourth of the total, and P&C building one-fifth of the total. Regarding energy intensity, P&C buildings and NUH occupied a higher percentage of the total. Therefore, it is fair to conclude that each category of building type occupied approximately one-fourth of the total energy use. Since the building stock and energy intensity of P&C buildings have increased rapidly in recent years, P&C buildings have become the largest building energy consumer group in the Chinese building sector.

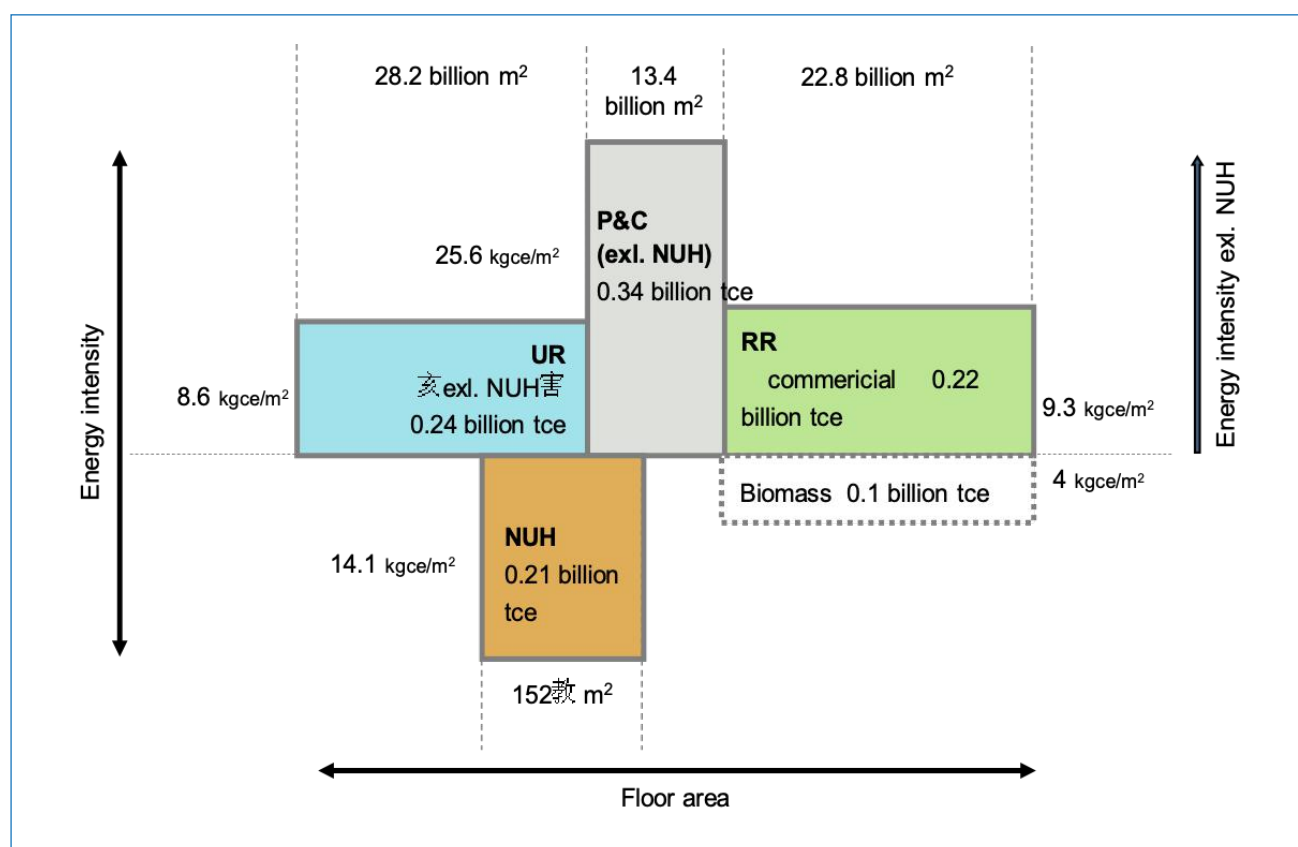


Fig. 2. Energy use of building operation in China (2019)

The shift in total energy use and energy intensity between 2008 and 2019 can be characterised as follows. While biomass energy use in rural areas decreased, energy use for all types of buildings increased significantly. The characteristics of the energy intensity of each type of building are described below:

- Although the energy intensity of NUH is relatively large, it has been decreasing in recent years, which was the result of energy efficiency improvement.
- Energy intensity continued to increase for P&C buildings. The increasing energy demand of different kinds of end users (air conditioners, devices, lighting, etc.) was the major cause of the increase in building energy intensity. In recent years, many large-scale P&C buildings have been constructed, with much higher energy intensity than other P&C buildings.
- The energy intensity of urban residential buildings increased continuously because there was more demand for domestic hot water, air conditioners, and household appliances, which led to more energy consumption. There was also a debate about heating methods in the HSCW zone. There was not too much increase in the energy use of lighting in residential buildings because of the adoption of energy-efficient illumination devices. The cooking energy intensity also remained basically unchanged.

Commercial energy intensity for rural residential buildings also increased. As the number of rural households and rural populations slowly decreased, commercial energy use in rural areas basically remained stable. However, as household appliances became more popular and the policy of “switching from coal to electricity” in rural areas, the power consumption intensity has increased dramatically in recent years. Meanwhile, the use of biomass has dropped continuously, and the total energy use for rural residential buildings has declined slightly in recent years.

## National policies

During the "12<sup>th</sup> Five-Year Plan" period, China has made significant progress in the energy efficiency of buildings and green buildings, improving energy efficiency standards, leapfrogging the development of green buildings, fully implementing energy-saving renovation of existing residential buildings in cold areas, further strengthening the supervision of energy-saving public buildings, steadily promoting energy-saving renovation in key cities and schools, hospitals and other areas, and further expanding the scale of renewable energy building applications, and successfully completing the work targets and tasks set by the State Council.

## Roadmap of building sector to achieve neutrality by 2060

There is currently no national roadmap for carbon neutrality in the building sector in China. But as one of the most important research centres in the energy and emission sector, the Building Energy Research Centre has conducted research on carbon neutrality roadmap planning. The research result is demonstrated below.

The dual carbon targets set forth by the central government are very clear and need to be achieved on time. Currently, the direct carbon emission of the building sector has already peaked, whereas the indirect one from electricity use and heating will peak by 2030. To achieve a carbon peak in the building sector at an early date, we recommend large-scale electrification transformation for building energy use and strengthening the energy efficiency of new buildings while retrofitting existing ones and promoting green living while practising frugality. To realise zero-carbon emissions in the building sector, we recommend building a new type of building energy system with distributed photovoltaic, distributed energy storage, low-voltage DC distribution network and flexible load control. Key technologies and related research on new rural energy systems based on distributed photovoltaic, combined with water and power generation based on recovered heat from nuclear and cross-seasonal heat storage need to be promoted and implemented at a faster pace.

## Best practices

We will demonstrate best practices in the above-mentioned technologies, including PSDF building (Photovoltaic, Energy Storage, DC system and Flexible energy demand), low carbon district heating systems in northern China, and other energy efficiency technologies in public and commercial buildings (including passive and active measures).

## Croatia

### Existing buildings

#### Energy partition between single houses, apartment buildings and office buildings

The energy balance for buildings was derived from the 2019 energy statistics on a national level, developed by Energy Institute Hrvoje Požar, which is published every year and publicly available<sup>1</sup>. To define the distribution of fuels between different end-uses, the Odyssee-MURE database was used<sup>2</sup>. *Table 1* shows energy consumption in buildings per sector and per fuel. Total energy consumption is 3.05 Mtoe, where the residential sector represents 73% and the service sector 27%. The most used fuels are electricity (34%) biomass (33%) and natural gas (22%). It should be noticed that biomass is dominantly used in the residential sector, around 1.01 Mtoe, which is equal to 46% of residential sector energy consumption.

	Total [TWh]	Oil [TWh]	Natural gas [TWh]	Biomass [TWh]	District heating [TWh]	Electricity [TWh]	Other [TWh]
<b>Residential</b>	25.82	1.16	5.35	11.75	1.28	6.16	0.12
<b>Service</b>	9.54	0.47	2.44	0.12	0.47	6.05	0.12
<b>Total</b>	35.00	1.63	7.79	11.87	1.75	12.21	0.24
<b>Share</b>	100%	5%	22%	33%	5%	34%	1%

*Table 1.* Energy consumption in buildings per sector and fuel

*Table 2* shows the energy consumption of the residential sector per use and per fuel. Unfortunately, such data is not available for the service sector. Space heating share is equal to 67% of total energy consumption, mostly covered by biomass and natural gas. Domestic hot water share is 10%, usually covered by electricity and natural gas. Electrical appliances, lighting and cooling together represent around 4% while cooking is 7%.

	Total [TWh]	Oil [TWh]	Natural gas [TWh]	Biomass [TWh]	District heating [TWh]	Electricity [TWh]	Other [TWh]	Share of residential sector [%]
Space Heating	17.33	0.70	3.84	11.16	1.16	0.35	0.12	67%
Domestic hot water	2.67	0.12	1.05	0.35	0.12	1.16	0.00	10%
Cooking	1.74	0.35	0.47	0.23	0.00	0.58	0.00	7%
Cooling	0.47	0.00	0.00	0.00	0.00	0.47	0.47	2%
Lighting	0.47	0.00	0.00	0.00	0.00	0.58	0.00	2%
Electrical appliances	3.02	0.00	0.00	0.00	0.00	0.00	3.02	12%

*Table 2.* Energy consumption per use and fuel for the residential sector

#### Which systems are mostly used for heating?

- Local systems (Furnaces, electric heating, heat pumps, solar thermal panels, geothermal systems, etc.)?
- Heat networks (hot water, steam). In this case, which energy sources are used? What is the CO<sub>2</sub> content per MWh<sub>th</sub>?

<sup>1</sup> National Energy Report developed by EIHP „Energija u Hrvatskoj 2019“ available here [http://www.eihp.hr/wp-content/uploads/2020/12/1\\_Energija\\_u\\_Hrvatskoj\\_2019-compressed-1.pdf](http://www.eihp.hr/wp-content/uploads/2020/12/1_Energija_u_Hrvatskoj_2019-compressed-1.pdf)

<sup>2</sup> Odyssee-MURE database available here <https://www.odyssee-mure.eu/>

As noticeable from *Table 2*, biomass is dominantly used for heating in the residential sector, especially in rural areas. Biomass is usually burned in furnaces or biomass boilers. In urban areas, natural gas boilers are dominantly used. District heating share is around 6%. It should be mentioned that around 80% of the use of district heating is in the capital, the City of Zagreb. District heating in Croatia is relatively old, with high-temperature regimes of the network (steam is also supplied to industrial customers). Larger district heating systems are based on natural gas cogeneration power plants, while smaller district heating networks use natural gas boilers. The carbon emission factor of natural gas boiler-based district heating systems is around 300 kg/MWh. The allocated carbon emission factor for natural gas CHP-based district heating systems is around 220 kg/MWh. Zagreb district heating network is currently being overhauled and a natural gas combined-cycle cogeneration plant is under construction.

### **Which systems are mostly used for cooling? (local systems, cooling networks...)**

Cooling is mostly covered with air-air heat pumps, while district cooling does not exist in Croatia. However, there are examples of utilising different heat sinks combined with heat pumps such as the ground/soil, groundwater or seawater but they are not common. Cooling represents a relatively small share in the residential sector, around 2%. It is assumed that this share is much higher in the service sector.

### **What are the main choices of national policy?**

Decarbonisation of the building sector is usually based on the energy-related refurbishment of existing buildings. The refurbishment rate is one of the lowest in the EU, around 0.7%, although national subsidies are usually granted both for the refurbishment of buildings and the integration of renewable energy sources, usually solar thermal and PV, for the residential as well as the service sector. Integration of heat pumps is not common but a plan for increasing their share is in place, according to the National Energy and Climate Plan. The most important issue is biomass, which is dominantly used in rural areas in inefficient stoves and furnaces.

### **Is there some roadmap for making existing cities more sustainable?**

Croatia does not have an official roadmap for sustainable cities. However, such a roadmap is promoted in the National Energy and Climate Plan, including the Recovery and Resilience Facility Plan.

Are there some case studies or best practices you would like to share?

The overhaul of the Zagreb district heating network is a large infrastructural project. The goal is to refurbish around 60 km of the network, equal to 1/3 of the overall length. The project value is 100 million EUR, while 60% comes from EU subsidies. This is also one of the highest EU subsidies awarded to Croatia.

The city of Vukovar has one of the most prominent district heating systems in the country. It is the first DH network which has successfully integrated solar thermal, with a relatively small share of around 5%. The plan is to expand this further. Besides biomass boilers and solar PVs, the plan is to invest in the first large-scale heat pump system for district heating purposes in Croatia while using the ground or groundwater as a heat source.

The old historical city centre of Dubrovnik has implemented seawater heat pumps for cooling purposes in several public buildings. The plan is to expand the system and connect additional customers. Generally speaking, blue energy for heating and cooling, through heat pump utilisation is becoming more popular and other coastal cities are investigating these possibilities.

## **New buildings**

### **Does your country have a national policy regarding new buildings?**

#### **Are some technologies prioritised?**

#### **How are they supported? Through regulations? Subsidies?**

The plan for increasing the number of nearly-zero energy buildings exists. Heating systems in these buildings are based on solar thermal collectors and air or ground-sourced heat pumps. Due to the high primary energy consumption of district heating systems, they are usually not a feasible option. In Croatia, CHP-based DH systems consume more primary energy per building or household than individual natural gas boilers. Currently, systems with lower primary energy factors are under development which should tackle this issue. District heating networks are expanded, but mostly in the City of Zagreb. However, there are no subsidies for DH

network connections. On the other hand, after the Zagreb earthquake, national subsidies for condensing natural gas boilers have been assigned.

### **Are there some recommendations and regulations for sustainable districts and cities?**

Most of the largest cities in Croatia have district heating systems. However, there is no heat zoning in place which would define neighbourhoods that should be connected to the district heating network. An obvious recommendation is to propose heat zoning for urban areas which would allow the definition of densely populated zones eligible for district heating networks.

As already mentioned, the primary energy factors for cogeneration-based district heating systems are higher than for individual natural gas boilers. This is unsustainable, especially when considering newly developed nearly-zero energy buildings which have defined primary energy-related criteria. The recommendation is to update the criteria for CHP-based district heating which would enable future expansion of thermal networks in urban areas.

Although the utilisation of natural gas in CHP is better than using it in boilers, it still represents a fossil fuel, which should be phased out in the heating sector by 2050. For this reason, large-scale integration of renewable energy sources in existing district heating systems is needed. The recommendation is to use locally available renewable energy sources in combination with heat pumps to reach needed supply temperature regimes. In parallel, a reduction of temperature regimes in the network is needed. This is achievable with building renovation and the development of low-temperature districts which could be separated from the main network with the shunt valve connection.

### **Are there some case studies or best practices you would like to share?**

The Zagreb earthquake in 2020 heavily damaged the historical city centre. Nevertheless, this presents an opportunity for the coordinated renovation of historical neighbourhoods, integration of renewable energy sources and expansion of the existing DH network. The City of Zagreb developed a case study of one damaged building block in the historical city centre which could be used as a lighthouse project for other neighbourhoods<sup>3</sup>. The project included connection to the district heating network, integration of heat pumps, solar PV and energy-related refurbishment of the buildings. However, at the time of writing this report, the project is still in the development stage.

---

<sup>3</sup> <https://www.zzpugz.hr/program-cjelovite-obnove-povijesne-jezgre-zagreba-izvjesce-i-plan/>

## Sweden

### Existing buildings

#### Energy balance 2019 (energy sources to end-uses)

Biomass	Coal and coke	Oil products	Natural gas, gasworks gas	Other fuels	District heating	Electricity	Total
15	0	11	2	0	45	72	144

*Table 1.* Final energy use in the residential and services sector by energy carrier, 2019, 144 TWh

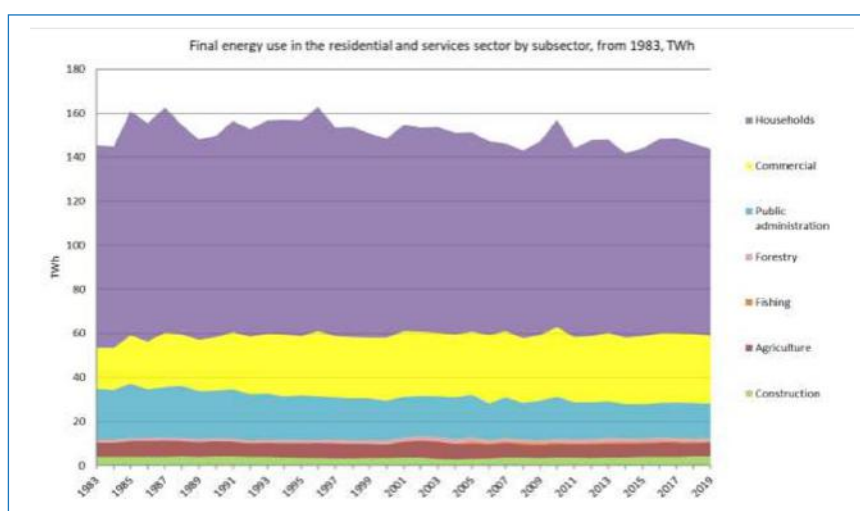
Construction	Agriculture	Fishing	Forestry	Public administration	Commercial	Households	Total
4	6	0	2	16	31	85	144

*Table 2.* Final energy use in the residential and services sector by subsector, 2019, TWh

Electric heating	Domestic electricity	Business electricity	Total
20,9	22,5	28,6	72,0

*Table 3.* Electricity use in the residential and services sector, 2019, TWh

See also *Figure 1.* below.



*Fig. 1.* Final energy use in the residential and service sector by subsector, 1983 to 2019

Electricity and district heating account for more than 80% of the energy used in the residential and service sector.

Electricity is the most common energy carrier for heating in houses, followed by biofuels and district heating. In multi-dwelling buildings and non-residential facilities district heating is by far the most common energy carrier.

The use of electricity in the residential and service sector increased considerably since the introduction of nuclear power in the mid-1970 to replace oil for heating.

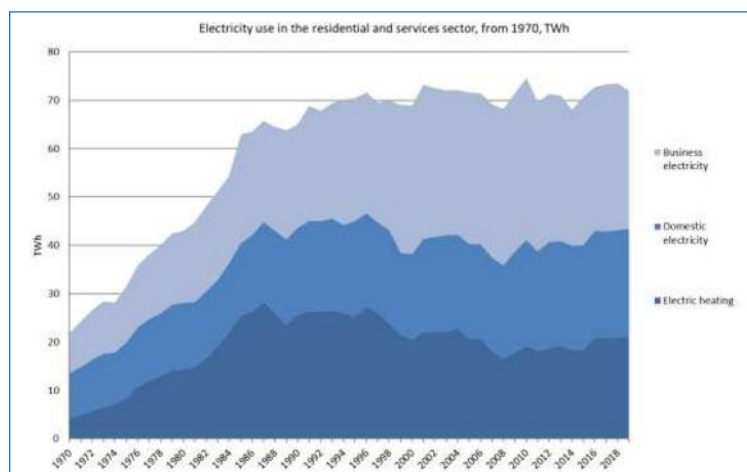


Fig. 2. Electricity use in the residential and service sector from 1970

### Energy partition between single houses, apartments buildings and office buildings

One- and two-dwelling buildings	Multi-dwelling buildings	Non-residential premises	Total
305	207	172	684

Table 4. Heated area in dwellings and non-residential premises, 2019, million m

Source: Swedish Energy Agency and Statistics Sweden. [energy-in-sweden-facts-and-figures-2021\\_210205-1.xlsx \(live.com\)](#)

### Which systems are mostly used for heating?

Electricity is the most common energy carrier for heating in houses, followed by biofuels and district heating.

The most common heating source in densely populated areas (from small towns up to large cities) is district heating.

Petroleum products can be used for heating but are mainly used for machinery in agriculture, forestry, fishing and construction.

- Local systems (Furnaces, electric heating, heat pumps, solar thermal panels, geothermal systems, etc.)?

Electricity accounts for around 50% of the energy used in the residential and service sector. Electricity direct heating and heat pumps are the most common systems. Solar panels are growing fast and are supported by national investment subsidies. But still, solar power only counts for around 1% of the total electricity generation.

- Heat networks (hot water, steam). In this case, which energy sources are used? What is the CO<sub>2</sub> content per MWhth?

District heating account for a little more than 30% of the energy used in the residential and service sector.

The heat market produces around 75 TWh yearly. Our well-developed district heating systems enable us to utilise energy resources that would otherwise be wasted, such as waste heat from industry and energy from the recycling of waste. Combined heat and power ensure the best possible use of these resources.

The CO<sub>2</sub> content per MWhth has decreased from around 325 kg/MWh in 1980 to 50 kg/MWh in 2019 thanks to the replacement of fossil fuels with biomass and recovered heat.

One- and two-dwelling buildings					
Oil	District heating	Electric heating	Natural gas	Boimass	total
0,4	5,5	15,3	0,3	8,8	30,2

Multi-dwelling buildings					
Oil	District heating	Electric heating	Natural gas	Boimass	total
0,1	23,6	2,1	0,2	0,1	26,1

Non-residential premises					
Oil	District heating	Electric heating	Natural gas	Boimass	total
0,3	15,9	3,6	0,3	0,4	20,4

Table 5. Energy use for heating and hot water in dwellings and non-residential premises, 2019, TWh

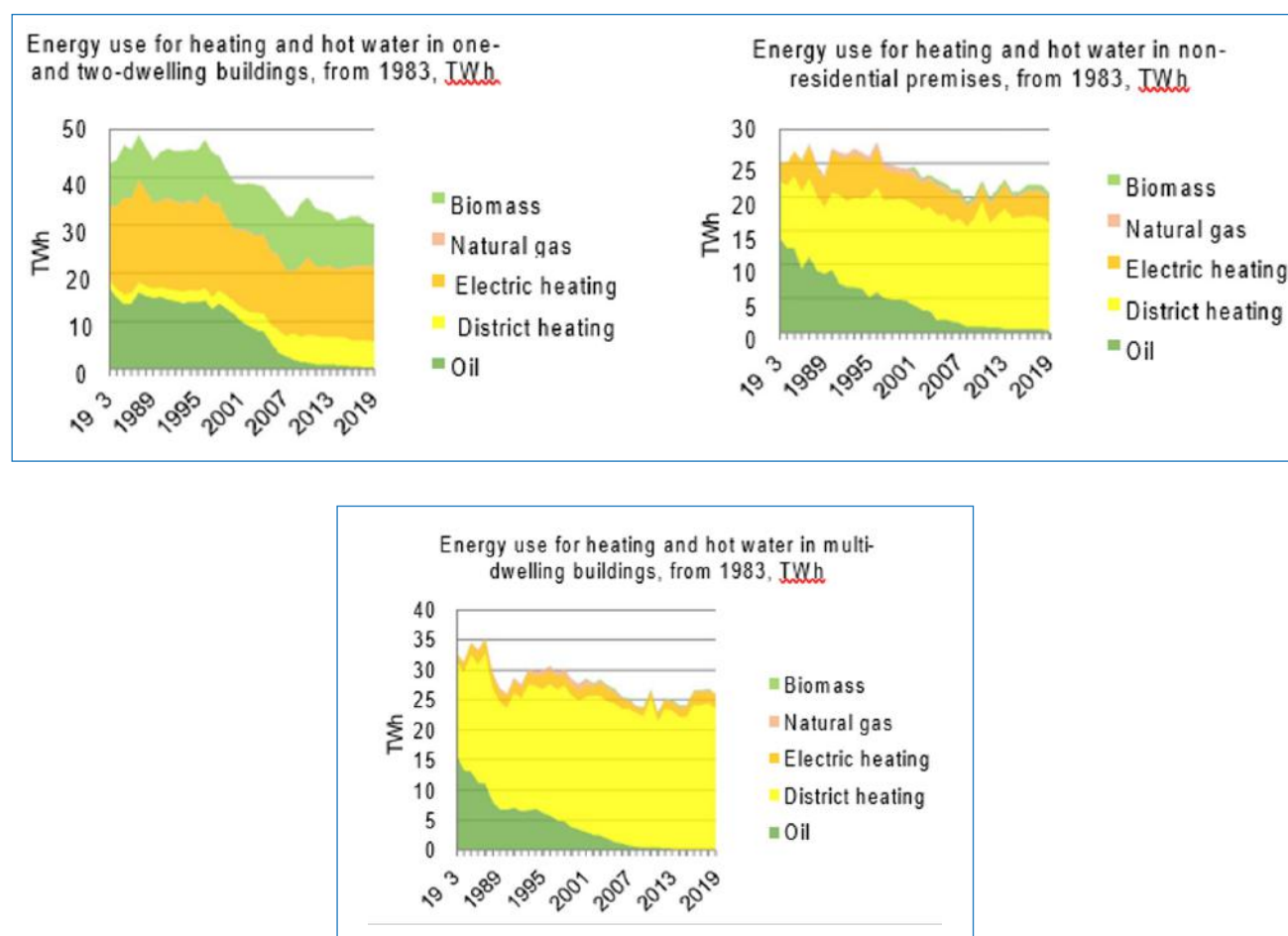


Fig. 3. Historical energy use for heating and hot water since 1983

Source: All figures and graphs from Sweden Energy Agency – Energy Facts and figures 2021. [energy-in-sweden-facts-and-figures-2021\\_210205-1.xlsx](https://www.svea.se/energy-in-sweden-facts-and-figures-2021_210205-1.xlsx) (live.com)

## What are the main choices of the national policy

– if there is one – to reduce the emissions from the existing stock of buildings? To make this reduction affordable.

A CO<sub>2</sub> tax which taxes fossil fuel for heating. There are also building codes for improving building performance and a building declaration system which requires buildings to have an energy declaration when they change owner.

- From a technological point of view? (Insulation, heat pumps, low CO<sub>2</sub> district network, geothermal systems, local PV production, etc.).
- From a regulatory point of view? Through land ownership regulations?
- Through subsidies, different financial mechanisms? Which are the priorities: reducing CO<sub>2</sub> or energy; Better inclusivity.
- Replacing parts of the existing stock of buildings?
- Is there a specific roadmap for this subject?

A **roadmap for fossil-free heating** has been developed in collaboration with about fifty actors in the heating market (district heating companies, heat pump companies, biofuel companies, property owners and builders, municipalities, county councils and regions). **The roadmap is part of the governmental initiative Fossil Free Sweden.**

The heating sector will be fossil fuel free by 2030. In 2045, it will be a carbon sink that helps in reducing the total Swedish greenhouse gas emissions.

To achieve this goal, the actors in the heating sector have, among other things, undertaken to:

- completely phase out the use of remaining fossil fuels and base also this district heating production on recycled energy;
- promote the development towards being fossil fuel free by setting ambitious energy and climate targets in municipalities, regions and county councils;
- sort and/or facilitate sorting of waste, especially plastics, to minimize fossil content in residual waste;
- through technology development, make heat pumps and system solutions more efficient to reduce electricity consumption and peak power requirements.
- The heating sector is ready to take on this challenge. This means that the industry needs to bind carbon dioxide emissions, for example by using CCS (Carbon Capture and Storage) technology. For the bio-based fuel, the impact could be climate-positive since carbon atoms that are already included in the natural cycle are removed. In addition, it can contribute to climate-negative emissions in Sweden as a whole. Furthermore:
- Create incentives for increased cogeneration of heat and power by valuing power and not just energy.
- Introduce policy instruments that provide incentives "Early in the chain", for example, already in product design and procurement, in order to turn plastics away from residual waste.
- Support research, development and demonstration of new technology such as bio- and waste-CCS, bio-coal, solar heat, seasonal heat storage, combined heat and power production with higher electricity exchange, small-scale combined heat and power technology, fourth generation district heating and recycling refinery for plastic waste.
- Ensure conversion from electric heating to district heating, heat pump or biofuel.

## Are there some case studies or best practices you would like to share?

- Test site for Bio-CCS in Stockholm is in operation since 2020 ([Bio-CCS - Stockholm](#) Exergi)
- An installation for the elimination of plastic waste from residual waste submitted for incineration is under construction in the Stockholm region.
- Several district heating companies are phasing out the last fossil fuels, for example the largest coal-fired combined heat and power plant in the country is decommissioned since 2020. Öresundsverket Malmö.

## New buildings

### Does your country have a national policy regarding new buildings?

If yes, what are the priorities? (For housing and for office buildings)

The construction and civil engineering sector, including the property sector, currently accounts for one-fifth of Sweden's climate impact.

Within the governmental initiative Fossil Free Sweden, a **roadmap for the construction and civil engineering sector** establishes goals to achieve a carbon-neutral value chain in the construction and civil engineering sector. Goals for the following years are:

2020–2022: Key players within the construction and civil engineering sector have mapped their emissions and established carbon goals.

2025: Greenhouse gas emissions clearly demonstrate a declining trend.

2030: 50 percent reduction in greenhouse gas emissions (cf. 2015).

2040: 75 percent reduction in greenhouse gas emissions (cf. 2015)

2045: Net zero greenhouse gas emissions

Source: [The construction and civil engineering sector - Fossilfritt Sverige](#)

### Are some technologies prioritised?

At the building level? At the infrastructure level? (Developing district networks, prohibiting connection to the gas network...)

The roadmap actors have committed to:

- intensify work on energy efficiency that reduces the heating and power requirement in newly produced and renovated buildings.
- push technology development in terms of reduced power peaks, energy storage, solar energy and solar heat.
- make better use of excess heat.

### How are they supported? Through regulations? Subsidies?

Investment subsidies for installation of solar cells at private properties

### Are there some case studies or best practices you would like to share?

1. Sustainable cities and smart cities <https://smartcitysweden.com/best-practice/>
2. Viva – Housing with Minimum Climate Footprint [BRF Viva – Housing with Minimum Climate Footprint | Best practice - Smart City Sweden](#)
3. Vallastaden – a Model for Sustainable Planning of Cities and Districts Vallastaden - [a Model for Sustainable Planning of Cities and Districts | Best practice - Smart City Sweden](#)
4. The Environmentally Sustainable City of Tomorrow in Malmö's Western Harbour [The Environmentally Sustainable City of Tomorrow in Malmö's Western Harbour | Best practice - Smart City Sweden](#)
5. H22 City Expo Showcases Big Ambitions for Building a Smarter City ([H22 City Expo Showcases Big Ambitions for Building a Smarter City | Best practice - Smart City Sweden](#))

## Uruguay

### National energy profile 2019

For a population of around 3.5 million inhabitants, the total consumption of energy in Uruguay was 72.3 TWh in the year 2020, 60% of which was provided by renewable energies. The electricity consumption was about 20%, provided at the rate of 98% by renewable energies such as hydro, wind, solar and biomass. Oil is mainly used in the transport sector. The use of biomass is highly relevant with the presence of about 40% of the energy consumed

### Energy perspectives 2030 - 2050

If possible, give the national perspectives for 2030 and 2050 or the roadmap to 2030 and 2050 if they exist.

### Does your country have national roadmaps regarding energy production and GHG emissions? What legal status do these documents have? What is their timeline?

There is a roadmap with a time horizon of 2030. The highlight is to produce a robust energy mix based on renewable sources, promote energy efficiency, and introduce electrical transport [<http://www.eficienciaenergetica.gub.uy/documents/20182/22528/Pol%C3%ADtica+Energ%C3%A9tica+2005-2030/841defd5-0b57-43fc-be56-94342af619a0>]. Moreover, a National Plan defining Energy Efficiency by 2024 is in place [<http://www.eficienciaenergetica.gub.uy/plan-nacional-de-eficiencia-energetica>].

### Roadmap for the energy mix

The mix of energies in Uruguay includes a strong contribution of renewables. Basically, they are the only native energy sources. The country has a plan to introduce electricity and hydrogen in the transport sector.

### Roadmap for the GHG emissions (country, per capita)

For a number of years, Uruguay is already developing a CO<sub>2</sub> inventory database [[https://visualizador.gobiernoabierto.gub.uy/visualizador/api/repos/%3Apublic%3Aorganismos%3Aambiente%3Avisualizador\\_inventario.wcdf/generatedContent](https://visualizador.gobiernoabierto.gub.uy/visualizador/api/repos/%3Apublic%3Aorganismos%3Aambiente%3Avisualizador_inventario.wcdf/generatedContent)]. The emission of CO<sub>2e</sub> was 20 Mt in 2020.

### Roadmap for the electricity mix

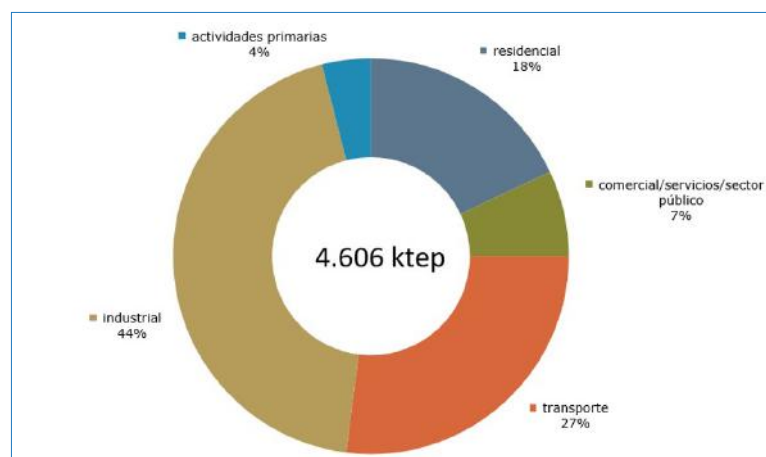
Uruguay has only renewable energies to increase supply. Solar power shows an incipient use with an installed power of 246 MW. All of the national territory is adequate to convert to this energy. The installed wind power is about 1 500 MW and basically, all the regions of the country are suitable for exploiting this energy source. The capacity could be increased to twice its present status without significant negative effects. The hydro resource is basically 100% exploited. Energy from biomass could still be increased significantly.

### CO<sub>2</sub> emissions from electricity production

The emissions of CO<sub>2e</sub> in the electricity sector were 6.215 Mt in 2020.

### Energy balance (energy sources to end-uses)

The following results were taken from the “National Energy Balance” ( 4.606 ktep = 53,7 TWh)



## Building sector

For some of the issues, there may be at present nothing concrete in place, but a collection of laws and decrees with related aims does exist.

## Existing buildings

Which systems are mostly used for heating?

- Local systems (Furnaces, electric heating, heat pumps, solar thermal panels, geothermal systems, etc.)?

Fireplaces and heat pumps. Between the fireplaces based on wood the open front has a high presence and also other close systems.

- Heat networks (hot water, steam). In this case, which energy sources are used? What is the CO<sub>2</sub> content per MWh<sub>th</sub>?

Wood and electricity. CO<sub>2</sub> emissions data are available for the total consumption.

## Which systems are mostly used for cooling? (local systems, cooling networks...)

Heat pump

## What are the main choices of the national policy

Specifically, there is no national policy to reduce emissions in the stock of buildings but there are some linked policies. The first one is the increasing introduction of renewable energies in the network. The second one is the promotion of high-efficiency biomass combustion systems for households. And a third one is the use of renewable energies in households with net tariffs.

Is there some roadmap for making existing cities more sustainable?

The actions in this sense are developed by the Government Department. As examples could be quoted: LED illumination, solid waste as an energy source, and the application of energy efficiency practice on the city hall installations. Also, as a joint task, the introduction of collective electrical transport.

Are there some case studies or best practices you would like to share?

A new test rig to test high-efficiency systems based on biomass for residential applications is available in the School of Engineering, Universidad de la República. The promotion of adequate electrical tariffs for use in households. The recommendation is to introduce devices with increased energy efficiency such as new electrical water tanks, biomass heating, and LED illumination, among others.

## New buildings

## Does your country have a national policy regarding new buildings?

The introduction of solar water heating in hotels, sports clubs, and health institutions on a national scale; the use of thermal insulation in new buildings is recommended by Montevideo City Hall.

Table of Contents

Argentina ..... 479

## Argentina

### Current situation

What is the energy balance (energy sources used)? And the GHG intensity, compared to other countries?

In the following tables, a summary of benchmarking data on refinery emissions is presented for various regions in the world. Data on emissions for various specific components (SO<sub>x</sub>, NO<sub>x</sub>, CO<sub>2</sub>), CEI™ (Solomon Carbon Emission Index™) and GHG emissions is included.

From this information, it can be seen that Latin America's situation with respect to the intensity levels of emissions from refineries is clearly worse than that of the leading regions in the world on this matter, namely US & Canada, Western Europe and the Middle East.

Percentage of Regional UEDC	Min	Top 25%	Top 50%	Top 75%	Max
<b>NOx ST/k UEDC</b>					
US and Canada	0.15	0.29	0.39	0.64	1.55
Latin America	1.25	1.62	2.20	3.07	8.83
Western Europe	0.37	0.58	0.84	1.29	4.93
Central and Southern Europe	0.40	0.55	0.70	1.02	8.08
Middle East	0.30	1.03	1.48	1.93	3.83
Asia/Pacific	0.11	0.53	0.83	1.27	12.07
<b>SOx ST/k UEDC</b>					
US and Canada	0.05	0.09	0.13	0.64	1.55
Latin America	1.48	3.48	4.67	13.28	29.24
Western Europe	0.16	1.09	1.66	2.53	7.56
Central and Southern Europe	0.08	1.18	2.03	4.16	13.95
Middle East	0.39	1.25	2.32	2.80	15.16
Asia/Pacific	0.05	0.43	0.64	2.54	14.99
<b>CO2 ST/k UEDC</b>					
US and Canada	707	935	1,037	1,151	1,596
Latin America	1,153	1,494	1,641	1,793	2,016
Western Europe	799	964	1,063	1,216	1,569
Central and Southern Europe	809	935	1,079	1,286	2,580
Middle East	726	916	1,033	1,258	1,450
Asia/Pacific	787	860	1,026	1,383	2,234

Table 1. Refinery Emissions- Percentage of Regional UEDC

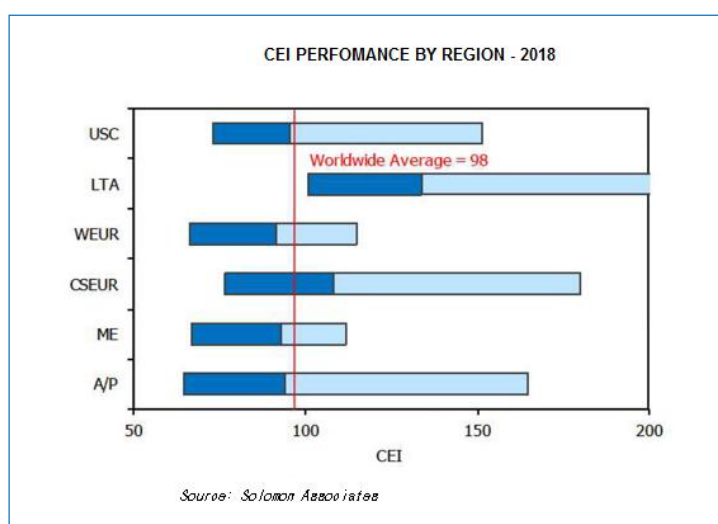


Fig. 1. Carbon Emission Index (CEI) Performance by Region – 2018 – Source Salomon Associates

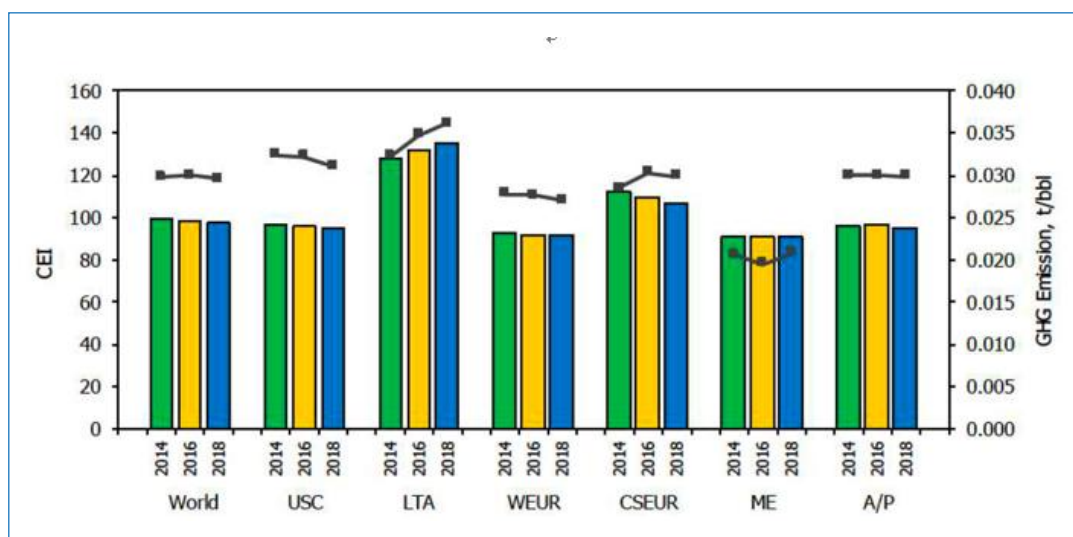


Fig. 2. CEI and GHG Emissions by Region Source: Solomon Associates

Technological and energy efficiency management developments continue to offer opportunities to reduce consumption and emissions in industrial facilities.

Refinery fuel gas (mainly methane, ethane, and by-products from refinery process units) is the main source of energy for burning in processes furnaces and steam generator boilers.

Electricity demand is satisfied mainly through onsite generation (from conventional steam boilers & generators, and/or cogeneration turbines with natural gas)

Burning of refinery fuel gas for process energy is at present the only method of disposing of this by-product stream. If this source of energy is not enough to satisfy the energy balance of the refinery, liquid fuels (diesel, fuel oil) or natural gas from the public network are used in addition.

#### GREENHOUSE GAS EMISSION FROM THE FUEL REFINING PROCESS

	Total ARG	Energy Sector	O&G (EPR)	Refining
Mton (CO <sub>2eq</sub> )	364	193	76	5
%	Base	33.00%	21.80%	1.40%
%	--	Base	10.8	2.60%
%	--	--	Base	6.60%

Table 2. Greenhouse Gas Emissions from the Fuel Refining process<sup>1</sup>

<sup>1</sup> Combustion activities supporting the refining of petroleum products, including on-site flaring for the generation of electricity and heat for own use.

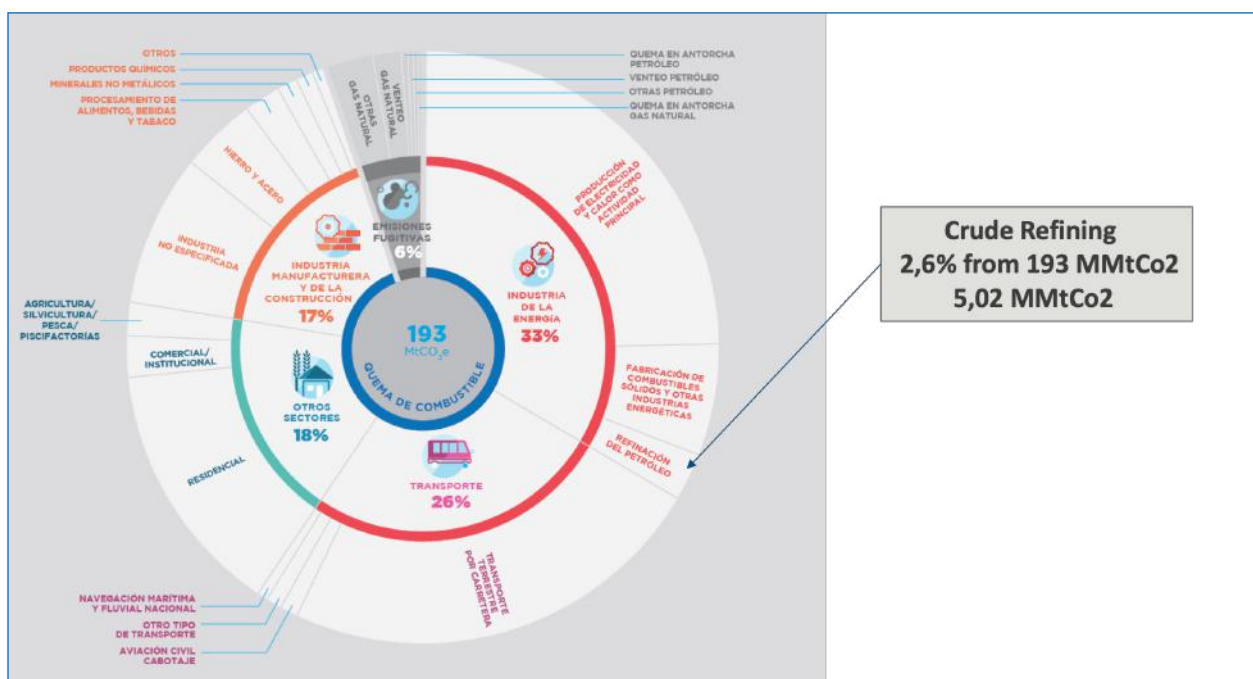


Fig. 3. Crude Refining impact in the total Argentina Energy GHG Emissions. Source Inventario Nacional del GEI 2019

## Are the best available low-carbon technologies used/considered?

The actions of Argentina's refineries to reduce emissions are:

### A. Energy & emissions efficiency in processes

- Improvements in heating equipment; improved heat integration of process streams; replacing combustion equipment / steam turbines / electric motors with more efficient ones; optimising operational and catalytic performance are all practices normally applied in the refining industry and can be further expanded. This is usually driven by means of the implementation of a site-wide energy management system.
- Thermal energy generation optimisation (e.g. replacement of steam boilers & turbines by cogeneration/combined cycle with higher generation efficiency)
- Flaring reduction programmes, tank vents recovery/recycle
- Extension of maintenance cycles of process units and utility complexes

### B. Use of low-carbon energy sources

- Replacement of liquid fuels by natural gas in process furnaces or steam generation boilers, resulting in reduced GHG emissions per energy unit released.
- Increasing the proportion of electricity supply generated from renewable sources (It is enforced by regulation).
- Is there a roadmap to decrease GHG emissions for 2030 - 2050 If yes, what are the intermediary steps?
- There is no road map defined by the government, but the private companies have an evergreen continuous improvement activity to increase energy efficiency and reduce oil losses resulting in GHG emission reduction as follows:
  - Heater hardware upgrading or replacement to improve energy recovery
  - Isolation maintenance programmes to reduce energy losses; compressed air and steam traps to minimise material loss
  - Improved heat integration of process streams
  - Efficiency optimisation of thermal energy generation via replacement of steam boilers and turbines by cogeneration

In the long term, for example, Yacimientos Petrolíferos Fiscales (YPF, ypf.com) is analysing how to implement new technologies to produce H<sub>2</sub> and electricity via renewable sources

- Major technology changes in Hydroprocessing by using natural bio raw materials instead of petroleum byproducts.
- Operation cycle extension including turnaround optimisation cycles
- Vapour and gas recovery systems to minimise venting or flaring

### **Is the implementation of low-carbon technologies helped by the government?**

**For refurbishing or replacing equipment? How are public authorities pushing the transformation? Through benchmarking? Audits?**

To date, there is no specific governmental programme or incentives focusing on the implementation of low-carbon technologies.

During the last years, the focus of government environmental policies for the refining industry in Argentina was oriented to fuel specifications (sulphur reduction in gasoline and diesel), resulting in the implementation of sizeable investment programmes in the different refineries in the country in this area.

Another investment focus during the last years in local refineries was on increasing conversion/processing capacity and adapting the refineries for processing the (increasingly available) Vaca Muerta shale crude oil and reducing product imports.

### **Are there incentives for carbon capture, utilisation, and storage? How?**

Currently, there are no governmental programmes or incentives in this respect

**If relevant, what about recycling? What percentage is recycled? What are the obstacles to increase recycling? Is a policy to increase recycling already in place or in project?**

Not applicable

### **Are there some case studies or best practices you would like to share?**

From Raízen Argentina we can share some examples of implementation in Refinería Buenos Aires on:

- Replacement of liquid fuel for natural gas in Boilers No. 10 and 11
- Programme to optimise the efficiency of the thermal energy generation park (electricity/steam)
- Recovery of flare gases via compressors
- Vapour recovery from light product tanks and truck dispatch islands

YPF Information

- Regarding GHG emissions, in 2018 the company undertook to reduce by 10% the intensity of direct emissions (scope 1 GHG) by 2023. It has in place an internal Emission Management regulation.
- Thus, a series of actions have been set in motion to optimise energy management, reduce vented and flared gas, expand electrification and digitalisation of operations, and incorporate low-carbon energy sources.
- The target is 10% reduction of direct GHG emissions intensity by 2023 from Base Year: 2017: 0.38 tCO<sub>2e</sub>/production unit.

To 2020: company GHG emissions intensity is 0,366 tCO<sub>2e</sub>/ production unit

Indicator	Unit	2020	2019	2018	2017
<b>Direct GHG emissions (Scope 1) KGJ</b>					
<b>Total direct GHG emissions (Scope 1) *</b>	<b>tCO<sub>2</sub>e</b>	<b>15 204 794</b>	<b>16 981 198</b>	<b>17 951 758</b>	<b>17 012 559</b>
Carbon dioxide (CO <sub>2</sub> ) emissions	tCO <sub>2</sub>	11 352 215	12 792 308	13 557 352	13 007 777
Methane (CH <sub>4</sub> ) emissions **	tCH <sub>4</sub>	147 393	159 857	167 426	152 868
Nitrous oxide (N <sub>2</sub> O) emissions	tN <sub>2</sub> O	563	646	701	614
<b>GHG Emissions by Business (Scope 1)</b>					
Upstream	tCO <sub>2</sub> e	8 685 380	9 991 616	10 565 160	10 570 443
Refining ***	tCO <sub>2</sub> e	2 751 091	3 448 653	3 511 116	3 554 540
Chemistry****	tCO <sub>2</sub> e	529 395	678 542	638 610	614 360
Logistics	tCO <sub>2</sub> e	142 699	1 460 217	190 044	171 561
Gas and Energy *****	tCO <sub>2</sub> e	3 081 476	2 689 022	3 033 476	2 087 814

\* Considering CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub>

\*\* They represent 24% of total emissions in 2020 and 2019; 23% in 2018

\*\*\* Corresponds 57% to the La Plata Refinery (Buenos Aires); 40% to the Luján de Cuyo refinery (Mendoza) and 3% to emissions from the Plaza Huincul Refinery (Neuquén)

\*\*\*\* 81% of these emissions correspond to the La Plata Chemical Complex (Buenos Aires) and the remaining 19% to emissions from the Methanol Silver of the Plaza Huincul Industrial Complex (Neuquén)

\*\*\*\*\* The increase is linked to the incorporation during 2020 of the operations of the Termicas de La Plata Cogeneración II (Buenos Aires) and El Bracho (Tucumán) plants

Table 3. GHG Emissions

Intensity of GHG Emissions	Unit	2020	2019	2018	2017
YPF (balanced)	tCO <sub>2</sub> /MWh electricity produced	0,366	0,374	0,382	0,380
Upstream	tCO <sub>2</sub> e/t Oil & Gas produced	0,400	0,410	0,420	0,410
Downstream	tCO <sub>2</sub> e/t Processed crude	0,290	0,310	0,300	0,290
Gas and Energy	tCO <sub>2</sub> /t Electricity emissions/t produced	0,340	0,350	0,360	0,390
<b>Upstream Methane Intensity</b>	<b>Unit</b>	<b>2020</b>	<b>2019</b>	<b>2018</b>	<b>2017</b>
	tCH <sub>4</sub> /t Oil & Gas produced	0,0068	0,0065	0,0066	0,0060

Table 4. Emissions Intensity

- Clean Development Mechanisms

YPF has implemented efficient processes in the different stages of crude oil refining to reduce GHG releases. For example, both in the industrial complex of La Plata and in that of Luján de Cuyo, waste gases are compressed and injected into the system to feed furnaces and boilers and avoid the use of natural gas and petroleum derivatives. Both complexes are recorded as “clean development mechanisms” (CDM) with the United Nations. The reductions achieved thanks to these processes were lower in 2019 due to failures and maintenance work on compressors.



Fig. 4. Reduction of GHG emissions by project

- Energy Efficiency

Downstream, the most relevant projects in 2020 were associated with the renovation of processing units in Luján Cuyo and La Plata. In this last complex, it also started operating a new cogeneration plant (89 MW), which will allow it to work on an island, feed surpluses into the interconnected system and have a more efficient supply of steam for the refinery.

Instead of producing steam by burning gas, steam is generated from the thermal energy of the exhaust gases from the turbine that produces electricity. In the future, processing of more unconventional crude oil will help to continue lowering the CO<sub>2</sub> intensity, since being lighter, it requires less energy to be transformed into a more efficient product.

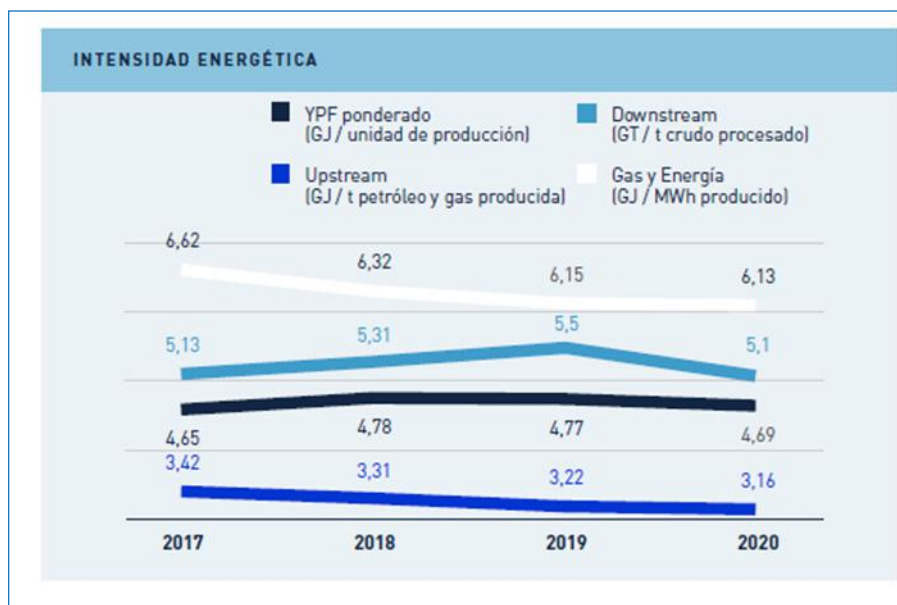


Fig. 5. YPF Energy Intensity

In case studies of DECARBONISATION OF ENERGY END-USES, YPF, through Y-TEC, is currently exploring technologies for the capture and use of CO<sub>2</sub> with the focus on circular economy

- Natural Solvents
- Capture through microorganisms and valorisation of biomass.
- CO<sub>2</sub> capture and use for water treatment of the operation.

At the same time, a space for collaboration between more than 40 companies active in the energy value chain, was launched in 2020 to develop a strategy for the development of the hydrogen economy for the country.



# CHEMICAL INDUSTRY ANALYSIS

## Table of Contents

---

Sweden ..... 486

## Sweden

### What is the energy balance (energy sources used)?

#### And the GHG intensity, compared to other countries?

In 2019, the chemical industry used approximately 12 TWh of energy (Swedish Energy Agency). Fossil and other fuels are the energy sources and account for 60 per cent. Other fuels include process and residual gases with fossil origin but originating from the chemical production processes themselves. The second largest share of energy comes from electricity. A small but increasing energy source comes from bioenergy.

GHG emissions were around 1,5 Mtonnes, which account for approximately 10% of the total industrial emissions.

### Are the best available low-carbon technologies used/considered?

#### If not, is it an economic problem? A matter of regulation? Or some social issues?

The chemical industry's transition pathway is described below.

- **Mechanical and chemical recycling of materials:** Through resource-efficient and circular material flows, a closed cycle for plastics can be created.
- **Transition to bio-based raw materials:** By using bio-based raw materials in the production process, the chemical industry can contribute to a developed bioeconomy and a greater share of bio-based materials. Bio-based raw material can, for example, come from rapeseed oil, straw, wood chips, algae, sugar cane and waste from the forest industry and agriculture. Methane in the form of natural gas is an important raw material in the chemical industry. Biogas fed into the natural gas network can be used as a bio raw material.
- **Transition to bio-based fuels:** Bio-based alternatives to fossil fuels can be used provided they are equivalent in terms of availability, function, quality and price.
- **Carbon capture and storage (CCS):** A step-by-step transition to bio-based raw materials and fuels in the processes provides the opportunity for negative emissions through CCS.
- **Recycling of CO<sub>2</sub> into new raw materials:** By recycling the carbon dioxide generated in production processes, it is able to enter as a raw material in production processes instead of being released.
- **Energy efficiency:** is an ongoing activity in the chemical industry. One way to achieve this is to facilitate the exchange of residual energies between industry and society, which promotes both lower CO<sub>2</sub> emissions and better use of resources.

### Is there a roadmap to decrease GHG emissions for 2030 - 2050

#### If yes, what are the intermediary steps?

Members of **IKEM – Innovation and Chemical Industries in Sweden** have identified ways to reduce emissions by ~85% by 2045 by combining five main strategies:

- **Climate-neutral energy:** A combination of electrification, hydrogen and biofuels replace today's fuels, often to produce heat with very high temperature.
- **Carbon capture and storage (CCS):** Capture, transport and storage of CO<sub>2</sub>
- **Bio-based raw materials:** Production of fuels and chemicals from bio-raw materials, often with completely new production processes and hydrogen needs as a complement.
- **Circular economy - recycled raw materials and CCU recycling by:** virgin raw materials are replaced by recycled plastics, metals or waste, or captured CO<sub>2</sub> is used in hydrogen as a raw material for the production of chemicals (CCU).
- **Resource-efficient systems:** Possibilities to use residues such as waste heat and development of industrial symbiosis.

**If relevant, what about recycling?**

**What percentage is recycled? What are the obstacles to increase recycling? Is a policy to increase recycling already in place or in project?**

However, an important difference is that one of the main measures is to work towards circularity. There are projects on developing waste-plastic refineries. If successful, this would in the long run make it possible to phase out the use of (fossil) oil as feedstock for producing new plastics. Instead, such recirculation processes will make it possible to transform the plastic back to its original building blocks (monomers) which is different to today's recycling which is based on simple thermochemical melting processes.

**Are there some case studies or best practices you would like to share?**

Projects with the aim to develop waste-plastic refineries are ongoing, e.g., cooperation between a chemical plant in Stenungsund and a university (Borealis and Chalmers).

As for the emissions from the refinery sites, the Preem refinery is planning to apply for CCS and has recently successfully carried out pilot tests with post-combustion capture at one of their refineries (Preem refinery in Lysekil). There are also projects on using hydrogen from electrolysis with electricity supplied by renewable electricity.

Table of Contents

China ..... 489

Croatia ..... 493

India..... 495

South-Africa ..... 508

Sweden ..... 510

## China

### What is the energy balance (energy sources used)?

### And the GHG intensity, compared to other countries?

The energy consumption in the cement production process mainly includes 2 parts. One is the electricity consumption for the production line, which is about 100 kWh/t for a typical 5 000t/d cement clinker production line. The other one is the fuel combustion for heat production for cement clinker calcination. In China, most cement production enterprises in China use coal as fuel, and the standard coal consumption in clinker calcination is around 100kg/t. 40% of the heat provided in this process is lost due to heat dissipation of the kiln barrel and the heat taken away by the kiln flue gas.

According to CO<sub>2</sub> emission factors of coal combustion (2.66 kg CO<sub>2</sub>/kg coal) and electricity production (0.8 kg CO<sub>2</sub>/kWh) in China, the CO<sub>2</sub> emission factor of energy consumption in the calcination process is 266 kg CO<sub>2</sub>/t clinker, the indirect CO<sub>2</sub> emission factor is 80 kg CO<sub>2</sub>/t cement. Another part of CO<sub>2</sub> emission in cement production is from limestone decomposition. 85% of the main raw material for cement is limestone. The CO<sub>2</sub> emission related to this is about 302 kg/t cement.

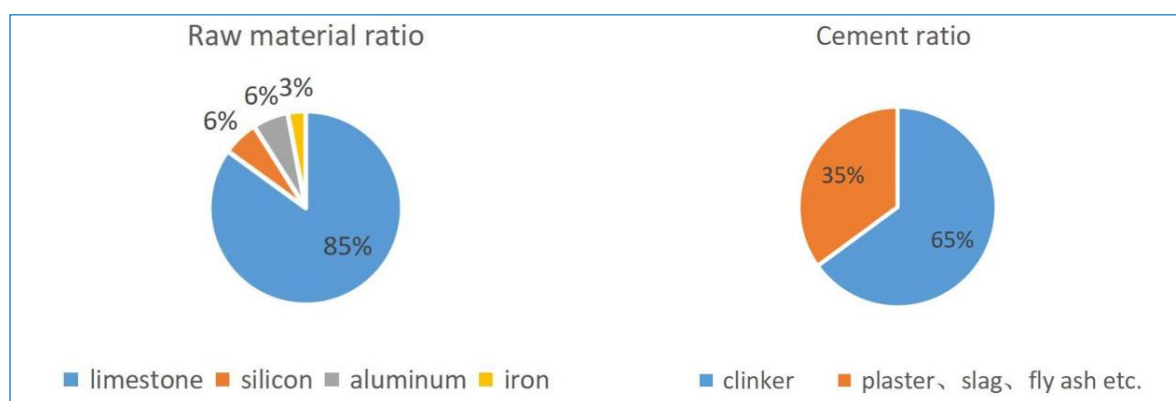


Fig. 1. a) (left) Raw materials used for cement production and b) (right): Composition of cement (ratio clinker/other materials)

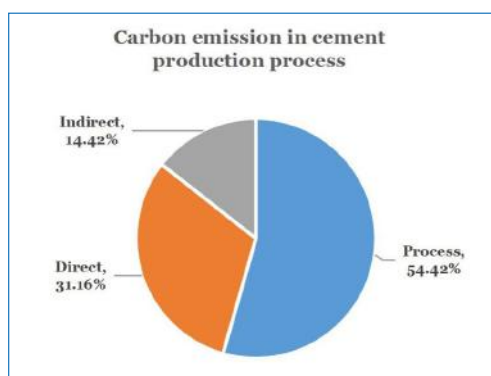


Fig. 2. CO<sub>2</sub> emissions in the different parts of the cement production process

In total, under current manufacturing technology, the CO<sub>2</sub> emissions per cement clinker production and cement (while the clinker content of cement is 65%) are 860 kg/t and 563 kg/t, respectively. Other greenhouse gases in the cement production process are negligible.

The carbon emission intensity is similar because of the similarity of the producing technology all over the world. However, it should be noted that in 2020, the cement production in China is about 2.4 billion tons, accounting for 53% of the world's total cement production.

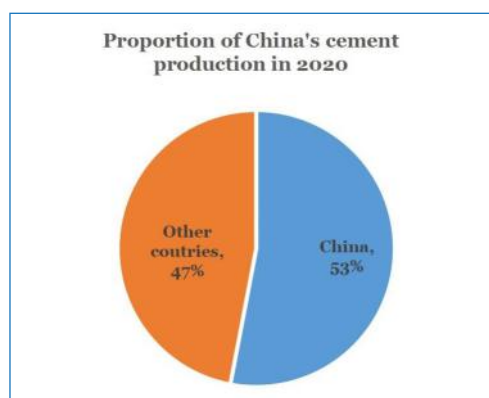


Fig. 3. China's share in worldwide cement production

### Are the best available low-carbon technologies used/considered?

If not, is it an economic problem? A matter of regulation? Or some social issues?

Energy conservation and emission reduction are highly emphasized in China's cement industry. The best technologies have been applied, including roller press or vertical mill grinding technology, pre-calcining kiln calcination technology and waste heat power generation technology. The carbon emission per unit of cement is significantly reduced with the improvement of energy efficiency.

Currently, the recommended technologies to reduce CO<sub>2</sub> emissions include alternative raw material technology, alternative fuel technology, low-carbon cement technology, etc. Calcium carbide slag has been used in some cement production factories instead of limestone to reduce carbon emissions. Partial replacement of limestone with steel slag has also been considered. However, it is limited by the supply of calcium carbide slag or steel slag. Alternative fuels, such as industrial solid waste, and crop straws, have been used by some manufacturers. However, the sources of these fuels as well as the cost of their application remain problems for massive implementation. Lots of research has been conducted on low-carbon cement development, including reducing the content of CaO in cement clinker, reducing the amount of clinker in cement, or developing new cement. It is expected that these technologies will be applicable in the next 3 to 5 years.

The Chinese government has enacted incentive policies for the comprehensive utilization of resources. The application of low-carbon technologies will attract more support for the development of a carbon market in China.

### Is there a roadmap to decrease GHG emissions for 2030 - 2050

If yes, what are the intermediary steps?

The Chinese government has committed to peak its carbon emissions before 2030 and achieve carbon neutrality by 2060 (hereinafter referred to as "peak carbon emissions, and carbon neutrality"). Some studies predict that China's cement industry will reach its carbon emission peak in the next two or three years.

The cement production will be around 2.45 billion tons at that time, and it will decrease to 1.8 billion tons by 2030 and 900 million tons by 2060.

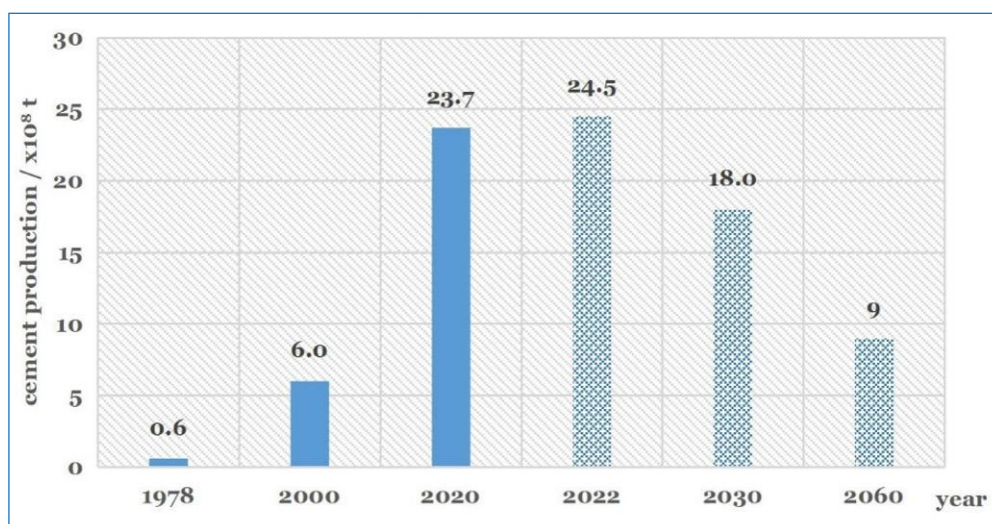


Fig. 4. A prediction of Cement Production in China

Currently, the National Development and Reform Commission and the Ministry of Industry and Information Technology of China are scheduling the national and industrial plan for the "Peak Carbon Emission and Carbon Neutrality" target. Some cement producers also make their own plans. For enterprises, alternative raw material and fuel technologies, low-carbon cement technologies or CCUS technologies are most considered. And they have also proposed a range of possible decreases in CO<sub>2</sub> emissions under different implementation scenarios in these plans.

The cement manufacturers, as the main body of CO<sub>2</sub> emissions, have an urgent need for CO<sub>2</sub> emission reduction technologies. Technology development at the industry level should be encouraged. It is also important to have more incentive policies at the national level.

### **Is the implementation of low-carbon technologies helped by the government?**

**For refurbishing or replacing equipment? How are public authorities pushing the transformation? Through benchmarking? Audits?**

The Chinese government, including the national government and provincial governments, are supportive of the implementation of low-carbon technologies, such as the application of energy-saving, emission-reduction and new technologies in the cement industry. The provincial governments have provided subsidies for waste heat utilization technology applications and equipment upgrading, etc., as well as incentives for integrated utilization of resources. The central government has developed energy efficiency rating standards for cement production enterprises for benchmark management, as well as assessment methods for CO<sub>2</sub> emissions for cement manufacturers, which provide motivation for promoting carbon emission reduction in these enterprises.

### **Are there incentives for carbon capture, utilisation, and storage? How?**

China is developing technology policies or incentive policies now.

### **If relevant, what about recycling?**

**What percentage is recycled? What are the obstacles to increasing recycling? Is a policy to increase recycling already in place or at the project stage?**

Cement will be mixed with aggregates such as sands and stones to prepare concrete for use in construction projects. Then the hydraulic reaction of cement happens during the application process when water is added. It is hard to recycle cement. However, there are currently studies going on regarding the use of construction waste (including cement hydration products) as raw materials for cement production.

**Are there some case studies or best practices you would like to share?**

In 2018, the CONCH company commissioned a CCS device to produce 50 kt/a

CO<sub>2</sub> ice with cement kiln gas. Another cement production company is planning to capture CO<sub>2</sub> for oil displacement or landfilling.

China has a large production capacity in the cement industry. The technologies are developing very fast. It is expected that a series of low-carbon technologies will be mature and applicable in the coming 3-5 years, which could further contribute to the low-carbon development of the world's cement industry.

## Croatia

### **What is the energy balance (energy sources used)?**

#### **And the GHG intensity, compared to other countries?**

There are three operating cement plants in Croatia. The production capacity of the Croatian cement industry is approximately 3.9 million tons of cement per year, and about 3 million tons of clinker, with an average clinker factor of 0.77. Regarding the energy balance in the Croatian cement industry, two balances need to be considered separately. The first one is the electricity consumption for the production line, which is about 113 kWh/t of cement. Here we need to emphasize that cement production plants in Croatia buy green electricity certificates that certify that the electricity has been produced by renewable energy sources. That means that there are no indirect CO<sub>2</sub> emissions from cement plants in Croatia. The second energy balance is fuel combustion. In this case, the fuel is used for heat production for the calcination process and clinker production. In Croatia, the average value of specific heat consumption is 3.4 GJ/t of clinker. The fuels predominately used are petroleum coke and coal, with an increasing share of alternative fuels like RDF (Refuse Derived Fuel), sewage sludge and waste oil. The total direct CO<sub>2</sub> emissions of the cement industry were about 2.5 million tons.

### **Are the best available low-carbon technologies used/considered?**

#### **If not, is it an economic problem? A matter of regulation? Or some social issues?**

In Croatian cement plants, the dry pre-calciner rotary kiln process is in use. Therefore, the best available technologies have been applied. Over the years by implementing this energy-efficient production process, the CO<sub>2</sub> emission per unit of produced cement has significantly been reduced.

Alternative fuels are used for around 20% of the total, like old tires, waste textile, RDF/SRF (Solid Recovered Fuels), sewage sludge and waste oil, bone meal etc..

### **Is there a roadmap to decrease GHG emissions for 2030 - 2050**

#### **If yes, what are the intermediary steps?**

Croatia as an EU Member State implements the EU Green Deal policy. The European Green Deal is a set of policy initiatives by the European Commission with an aim of making Europe climate neutral in 2050. An impact-assessed plan will also be presented to increase the EU's greenhouse gas emission reduction target for 2030 to at least 50% and towards 55% compared with 1990 levels. This implies that cement manufacturing will have to reduce its emissions. All EU cement manufacturers, including Croatian manufacturers, are taking part in the EU Emissions Trading System (EU-ETS). EU-ETS is seen as a cornerstone of the European Union's policy to combat climate change. The current price of CO<sub>2</sub> allowance at a level of 60 EUR/t is pushing cement manufacturers in the EU to implement their own plans for using alternative raw material and fuel technologies, low-carbon cement technologies or CCUS technologies.

### **Is the implementation of low-carbon technologies helped by the government?**

#### **For refurbishing or replacing equipment? How are public authorities pushing the transformation? Through benchmarking? Audits?**

The Croatian government is implementing the EU Green Deal policy in the local economy, including the cement industry sector. It is implementing the policy by supporting energy efficiency improvements, low-carbon technologies, and emission reduction technologies in the cement industry through structural projects. These structural projects offer funding to cement producers for improving their production process. These are close cooperation projects with research institutes, that offer the possibility to cement manufacturers to transform their production to be more environmentally efficient.

### **Are there incentives for carbon capture, utilisation, and storage? How?**

Currently, there are no incentives for carbon capture, utilisation, and storage projects in Croatia.

**If relevant, what about recycling?**

**What percentage is recycled? What are the obstacles to increasing recycling? Is a policy to increase recycling already in place or in the state of a project?**

Under Croatian and EU legislation, construction waste materials are defined as special waste that needs to be handled in a special procedure. The processing of waste concrete, asphalt and other construction waste materials lead to valuable raw materials and buffer materials that are used exclusively in road construction instead of new stone materials from the quarry. This reduces the need for raw materials in the road construction industry.

**Are there some case studies or best practices you would like to share?**

NEXE Ltd., a Croatian cement producer, made an environmental assessment study in 2021, in which the enterprise elaborates on the next steps in going 100% to alternative fuels. The share present share of 18% of alternative fuels will be increased in several stages to 100%. Petroleum coke and coal, the two fossil fuels that are now predominately used as sources for heat production, will be replaced by RDF, sewage sludge and waste oil in the coming years. The plan is that in the coming 3-5 years, only alternative fuels will be used in cement production, fostering the circular economy and decreasing the rate of waste landfilling in Croatia. This will contribute to the low-carbon economic development in Croatia.

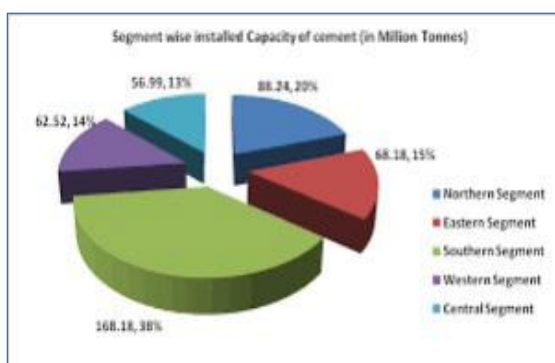
## India

### What is the energy balance (energy sources used)?

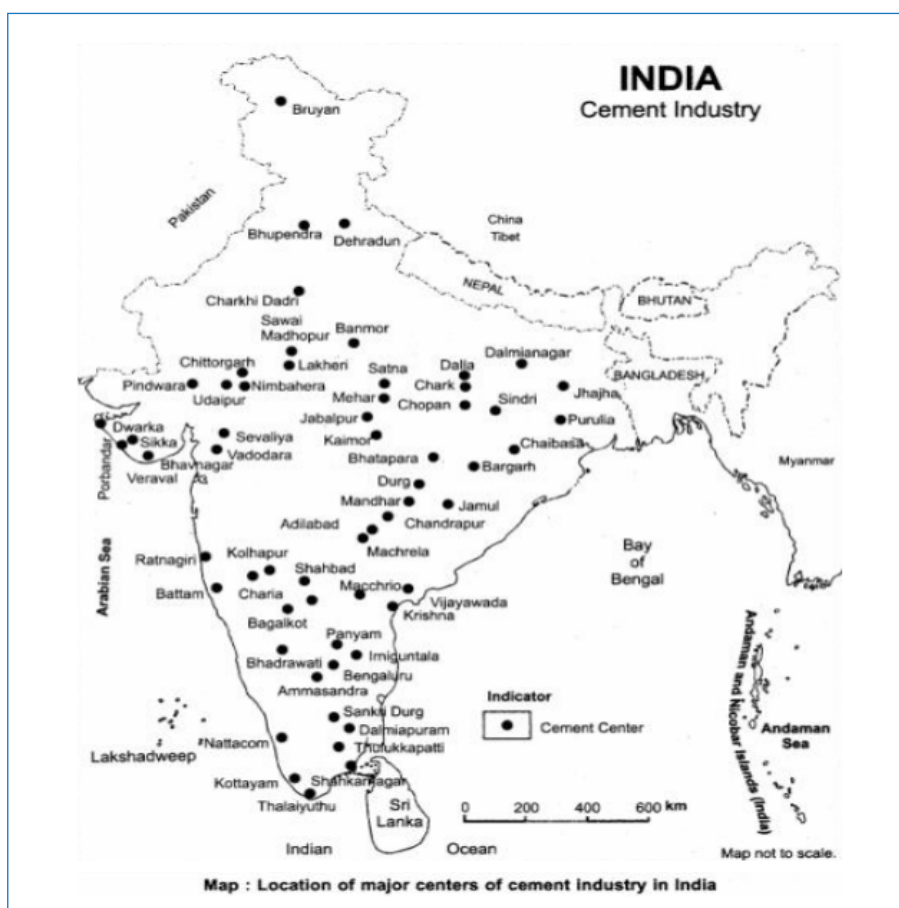
### And the GHG intensity, compared to other countries?

The Indian cement industry is one of the best-performing industries across various industrial sectors in terms of energy efficiency, quality control, environmental sustainability, and adaptive to venturing into new technology.

India is the second largest producer of cement in the world. India's overall cement installed capacity was nearly 545 million tonnes (Mt) in FY20 whereas actual cement production (demand based) was 294.4 million tons (Mt) in FY21. Cement production in India is expected to reach 550-600 Million Tonnes Per Annum (MtPA) by 2025 and 800 (MtPA) by 2030 and will continue to grow due to the continuation of the massive infrastructure and housing programme. The largest cement manufacturer in India has a consolidated capacity of 102.75 MtPA distributed all across India, as the cement plants are located all over India.



**Fig. 1.** Installed cement capacity in India by geographical area



**Fig. 2.** Location of major centres of the cement industry in India

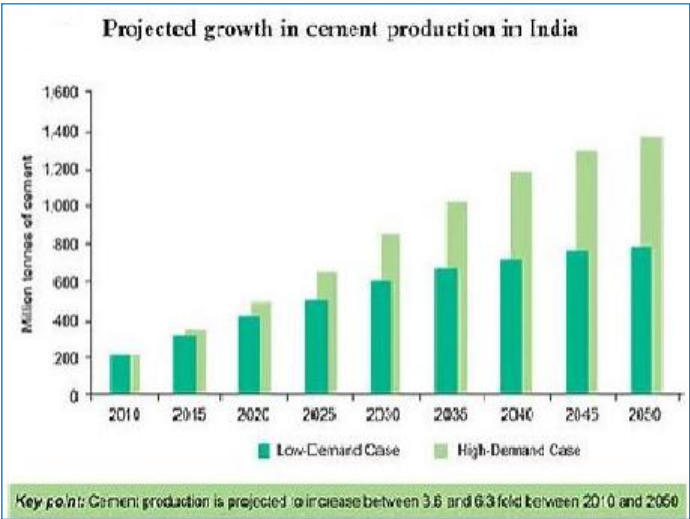


Fig. 3. Projected growth in cement production in India

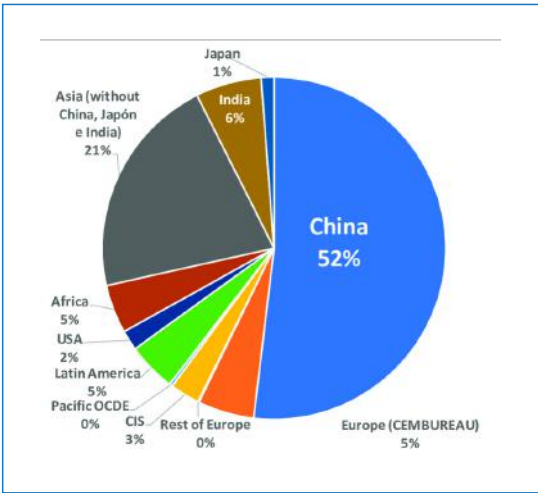


Fig. 4. World cement production in 2016

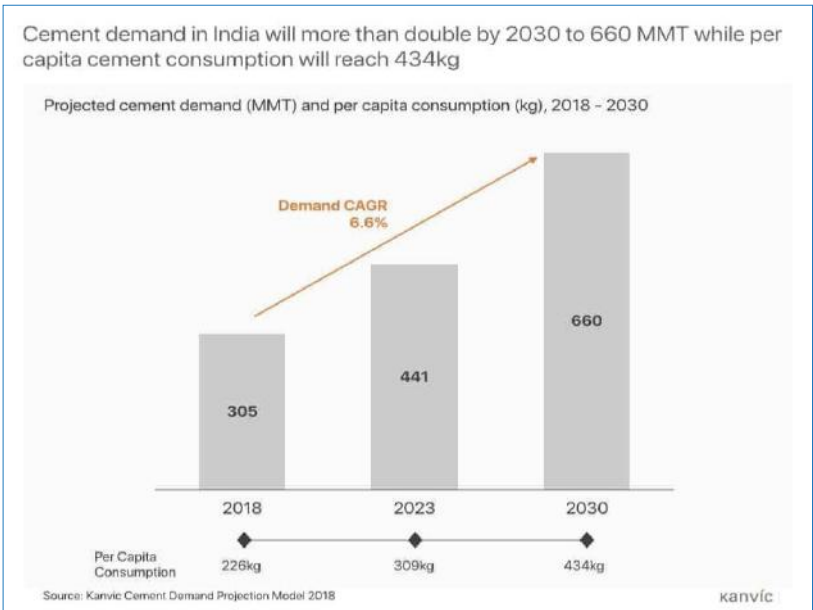


Fig. 5. Growth of cement demand in India from 2018 to 2030

## India – Energy supply by fuel

Cement is one of the energy-intensive industries. The Indian cement industry is a trendsetter in the world of cement and has been consistent in adopting the latest technologies for energy conservation.

At the present time, coal represents the major source of cement thermal energy consumption in India, due to its widespread availability, high heating value and low cost. Natural gas and oil are also used as fuel.

The best energy consumption levels achieved across Indian cement plants are 676 kcal per kg clinker and 64 kWh per Mt of cement whereas the average energy consumption levels are 740 kcal per kg of clinker and 76 kWh per Mt of cement.

Alternative fuel used by the cement industry is defined by the Thermal Substitution Rate (TSR), which refers to the percentage of alternative fuel used to replace fossil fuels. From the TSR level of 4% in 2016 (it was 0.6% in 2010), the Indian cement industry targets to achieve 25% TSR by 2025 and 30% by 2030.

India has joined hands with Switzerland and other European countries to reduce energy consumption and develop newer methods for more efficient cement production.

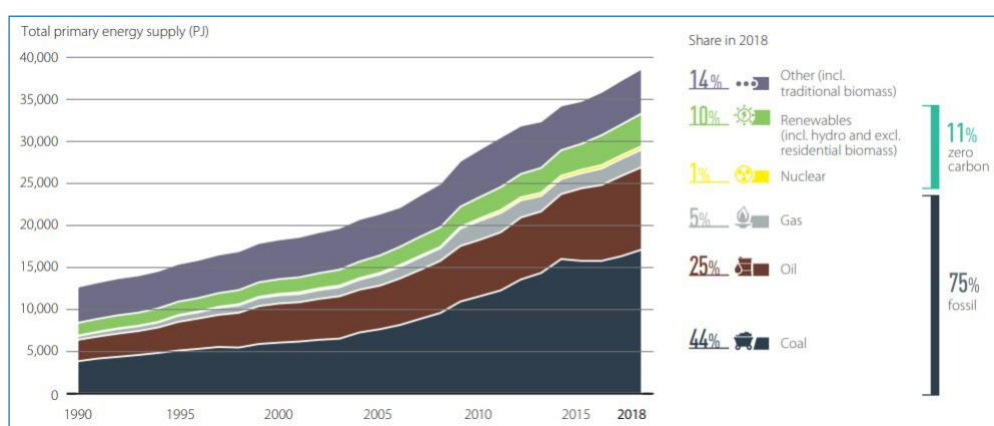


Fig. 6. Energy mix in the Indian Cement Industry

Currently, the industry is focusing on increasing the sources of renewable energy.

## Potential Renewable Energy Projects in Cement Plants

India ranks 3rd, behind U.S. and China, among 40 countries with a focus on renewable energy. The government has decided to substantially alter the energy mix that powers India in the future, such that, by 2030, at least 40 per cent of India's total power capacity will come from renewable sources.

### 1. Waste Heat Recovery System (WHRS)

WHRS has the potential to generate about 20% to 30% of plant power requirements (reducing purchased/captive power needs) using the Steam Rankine cycle/Organic Rankine cycle/Kalina cycle.

Energy saving potential		
Electrical	4.4	kWh per tonne of clinker
	2.3	kWh per mt of cement after grinding and packing
	5.3	kWh per mt of total cement
Thermal	4.0	kCal per kg of clinker

Table 1. Energy saving potential

Cement plants in India have installed WHR plants with a total capacity of 400MW (up to PAT Cycle II), with a potential of around 1,200 MW. By generating 400 MW of WHR-based power, around 2.2 Mt of coal have been

saved. This saving of fossil fuel is the reason these projects were considered under the Clean Development Mechanism (CDM) of the United Nations Framework

Convention on Climate Change (UNFCCC).

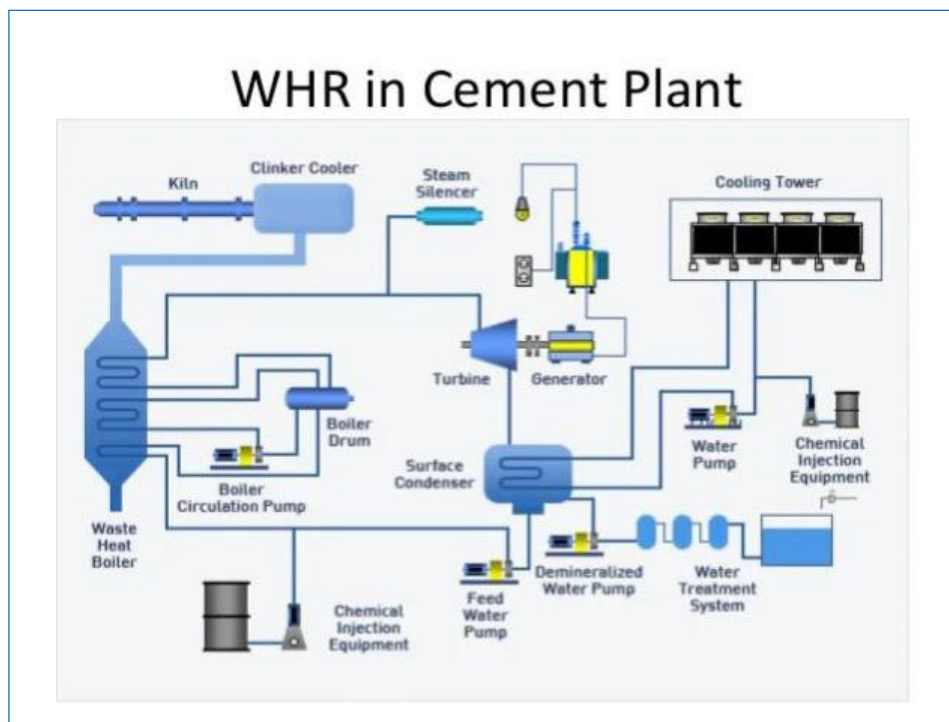


Fig. 7. Waste Heat Recovery in Cement Plant

Major Indian cement companies are planning to set up 175 MW of waste heat recovery system (WHRS) by 2022. It has emerged as one of the cheapest sources of power generation given the negligible input costs.

## 2. Solar Energy

By installing solar power plants and water heating systems, cement plants can meet obligations under both Renewable Purchase Obligation (RPO) and Performance Achieve and Trade (PAT) mechanisms as well as a reduction in greenhouse gas (GHG) emissions.

Most cement plants in India are located in dry and hot areas with enormous solar radiation and have huge amounts of unused, un-shaded arid land, ideal for the deployment of solar power plants. Solar energy can be harnessed either by Solar PV or Solar Thermal (CSP-Concentrated Solar Power) Technologies.

**Solar PV Plant-** Based on the typical brown-field 3 000 TPD cement plant, the available rooftop could harness solar power of appx. 1.8-1.9 MW (Open space for ground solar PV is separate).

**Solar thermal (CSP) technology** - can be integrated with existing (steam cycle) based plants (Coal, nuclear, CCGT, biomass) at various stages in the process (feed water heating, direct steam generation) and augment conversion efficiency.

## 3. Windmills

It is also used by a few Indian cement manufacturers in coastal areas, as an alternate source of energy.

## GHG emissions

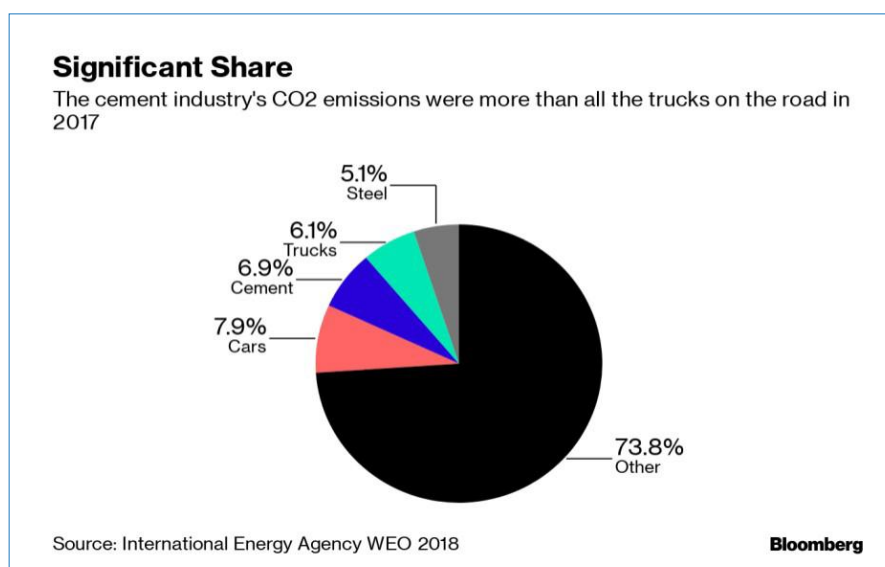
The cement sector is the third largest industrial source of pollution, emitting more than 500,000 tons per year of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub>.

Fuel emissions account for approximately 35% to 40% of total CO<sub>2</sub> emissions from cement manufacturing. The Indian cement industry is responsible for 8% of the total national emissions. These emissions are a product of electricity usage (13%), combustion of fossil fuel (coal, gas etc. for energy use) (31%), and the conversion process of limestone into lime (process emissions) (56%). The CO<sub>2</sub> emission intensity of the Indian cement in-

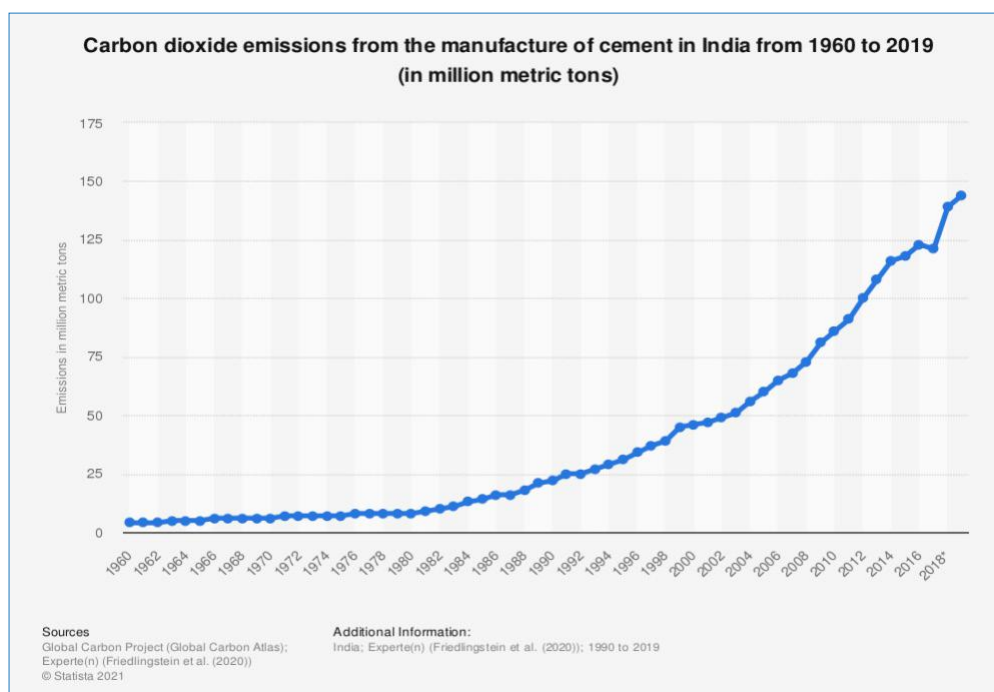
dustry in 2018 was 576 kg CO<sub>2</sub>/ton of cement produced whereas the global average is 634 kgCO<sub>2</sub>/ton of cement produced.

Indian cement industry has achieved a reduction of CO<sub>2</sub> emission factor from 1.12 t of CO<sub>2</sub>/t of cement in 1996 to 0.670 t of CO<sub>2</sub>/t of cement in 2017, enhanced blended cement production from 68% in 2010 to 73% of total cement production in 2017.

The adoption of Waste Heat Recovery Systems (WHRS) by cement plants in India has offered mitigation of greenhouse gas (GHG) emissions.



**Fig. 8.** Cement – significant share for global CO<sub>2</sub> emission



**Fig. 9.** CO<sub>2</sub> emissions from cement production in India from 1960 to 2019 (Mt)

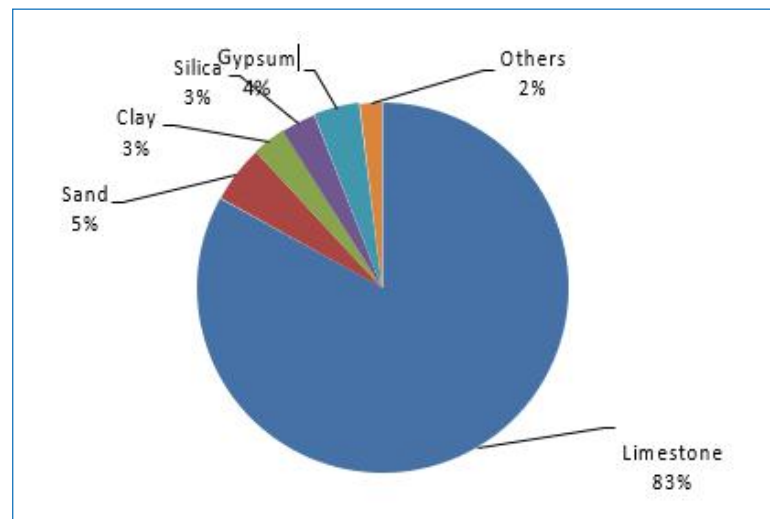


Fig. 10. Raw materials Ratio- India

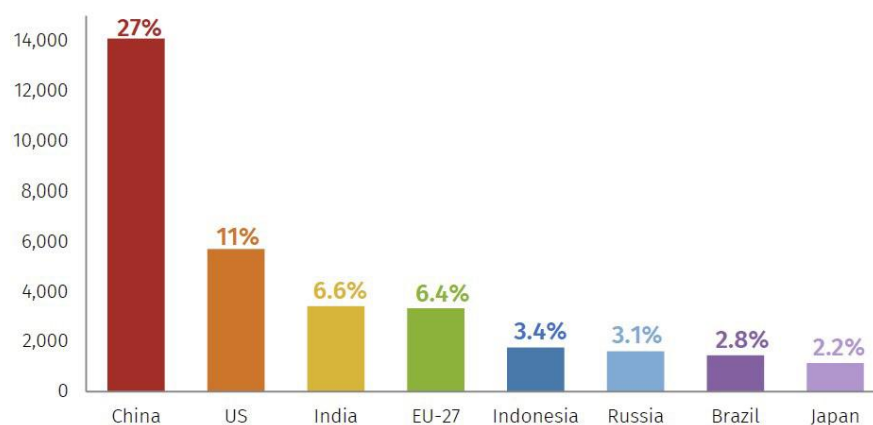
2018 League Table Rank	Company	League Table Weighted Rank
1	Dalmia Bharat	4.64
2	Ambuja Cement	5.62
3	Cementos Argos	5.90
4	Shree Cement	5.91
5	Lafarge Holcim (LH)	6.03
6	Heidelberg Cement	6.08
7	CRH	6.85
8	ACC (working with LH)	7.02
9	Ultra Tech Cement	7.32
10	CEMEX	8.04

Table 2. Carbon Disclosure Project (CDP) Global Cement Sector Ranking

Five Indian cement Companies (highlighted) are among the top 10 world ranks on business readiness for a low-carbon transition. An Indian company has recently been qualified “Climate Defenders” in recognition of the CDP on low carbon economy and commitment to a negative carbon footprint cement production by 2040.

### 2019 net GHG emissions from the world's largest emitters

Million metric tons of CO<sub>2</sub>e, including emissions and removals from land-use and forests and share of global total



Source: Rhodium Group

Fig. 11. Largest Greenhouse gas emitters worldwide, 2019

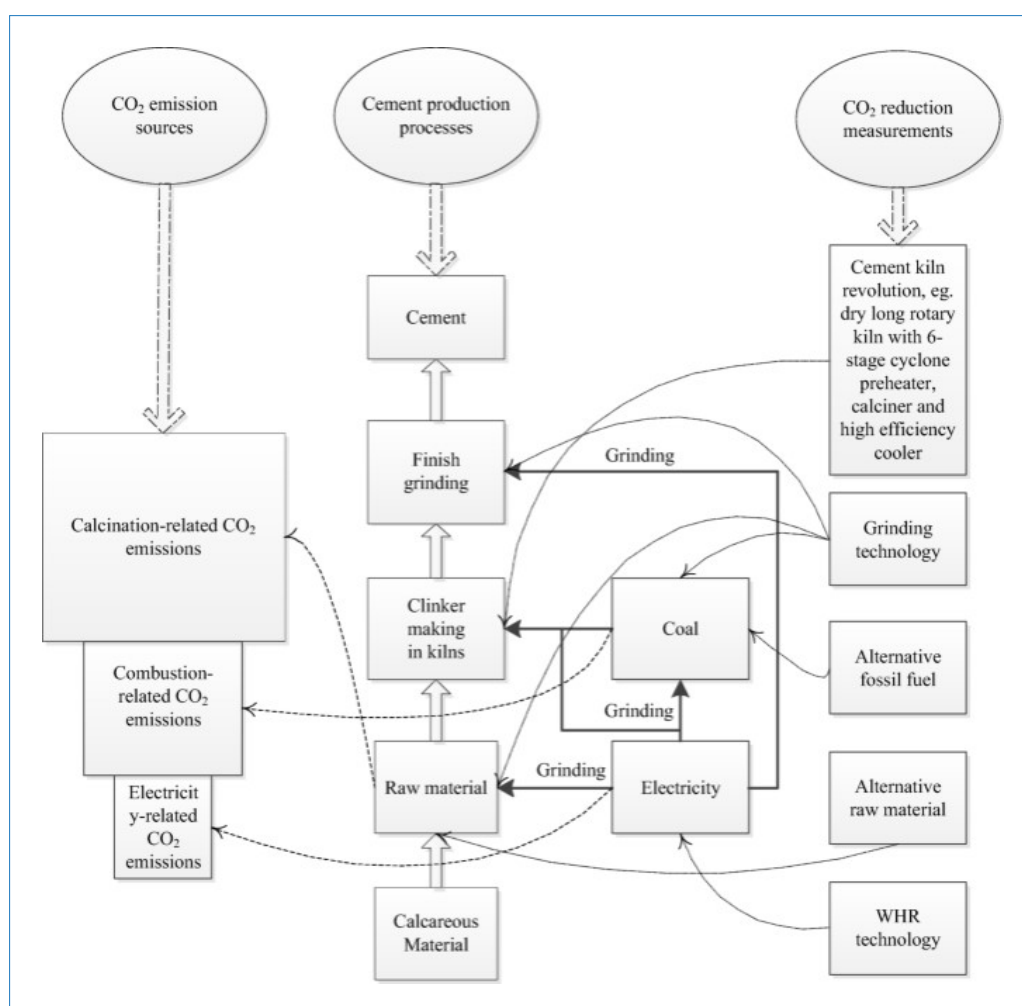


Fig. 12. Evaluation and mitigation of cement CO<sub>2</sub>

## Are the best available low-carbon technologies used/considered?

### If not, is it an economic problem? A matter of regulation? Or some social issues?

Energy Efficiency (EE) is a strong motivator for decarbonisation. Currently, cement plants in India are among the most efficient ones in the world in terms of energy conservation and in emission reduction, because India's large cement industry has phased out old technologies along with the following improvements (operations and energy consumption):

1. Kiln thermal efficiency improvements.
2. Milling/grinding electrical efficiency improvements.
3. Low-carbon fuel utilization– (wind, solar or biomass)
4. Lower-carbon cement or Portland-Limestone Cement (PLC)
5. Clinker-to-cement ratio reductions by mixing clay, blast furnace slag, fly ash etc.

Selected Indian cement companies are currently working on at-plant carbon capture and sequestration and utilization in association with European companies.

#### Economic Problem:

- High investments and operational costs.
- Minimal demand for green products, for consumers being unwilling to pay a premium for these products.
- Awareness of the benefits and confidence in the technical aspects is lacking.

**Social problem:** Co-processing using hazardous waste in cement industries has been encouraged, in the right environmentally safe manner.

**Regulations:** Certain incentives have been leveraged for green products. For Carbon Capture and Utilisation projects, an adjustment of a border tax has been given to encourage deployments.

India started to address climate change issues through its comprehensive National Action Plan for Climate Change (NAPCC). Gaps in the regulatory and policy framework create barriers to an effective transition to green technologies. Also, policy-targeted incentives and support measures are needed to increase the demand and supply of green alternatives.

## Is there a roadmap to decrease GHG emissions for 2030 - 2050

### If yes, what are the intermediary steps?

Each ton of cement generates approximately 0.7–0.93 tonnes of CO<sub>2</sub> depending on the kiln technology used. The top 10 cement-producing countries along with the European Union emit 1 445 million tonnes of CO<sub>2</sub> each year.

Indian cement companies are not required by regulations to make climate commitments or plan roadmaps for their emission reduction, they have done so at the top level of the cement industry through voluntary actions. Some of them are listed below:

1. Construction of the largest Carbon Capture and Utilisation (CCU) facility at a plant site with new technologies from the UK and Europe. Indian industries are leading some of the largest projects exploring CCUS technologies. They have recognised the role of CCUS during the transition period and the adoption of CCS/CCUS technologies should therefore be promoted in India.
2. Ambitious target of becoming carbon-negative by 2040.
3. India plans to reduce its carbon footprint by 33-35% of its 2005 levels by 2030.
4. Aiming to increase the percentage of renewables in its overall electricity consumption – with a target of 100% RE by 2030.
5. Doubling energy productivity by 2030
6. Recycling of waste and by-products for energy and raw materials
7. Reduce clinker-to-cement ratio.
8. Driving the transformation of hard to decarbonise and energy-intensive sectors along with other countries in the European Union.
9. Commitment to Science-Based Targets (SBTs)

10. Developing third-party assured integrated reporting based on the International Integrated Reporting Council (IIRC) framework.
11. Indian cement industry's Vision 2030: Building a New India
12. Use of digital technology, data science and performance-based measurement to assure optimum economic processes and fulfil the commitments.
13. Use of Carbon Cure Concrete – Carbon Cure Technology (CCT) – introduces recycled CO<sub>2</sub> into fresh concrete to reduce its carbon footprint without compromising performance. Once injected, the CO<sub>2</sub> undergoes a mineralization process and becomes permanently embedded.

This technology is encouraged for reducing concrete industry CO<sub>2</sub> emissions globally by 500 million metric tonnes annually by 2030.

Besides CCT the reduction in consumption of concrete products reused concrete and concrete products could be used on a large scale to reduce carbon emissions.

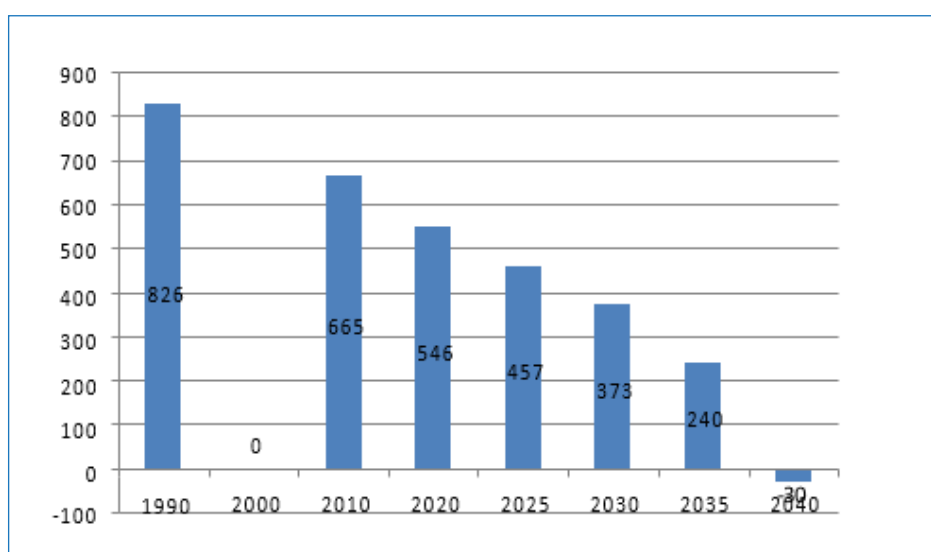


Fig. 13. India - Roadmap for carbon negative transition in selected companies

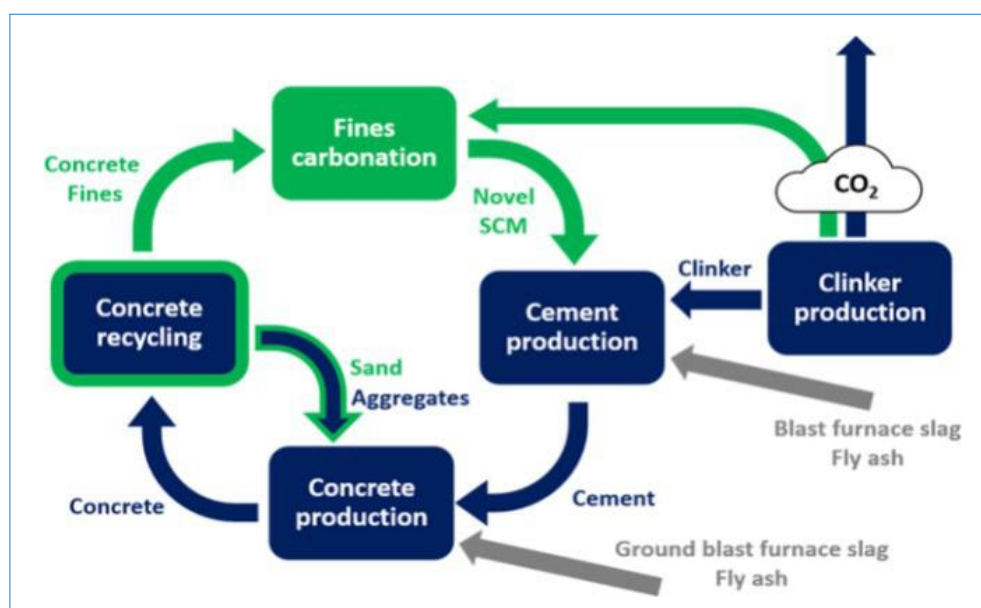


Fig. 14. Concrete recycling in production of cement

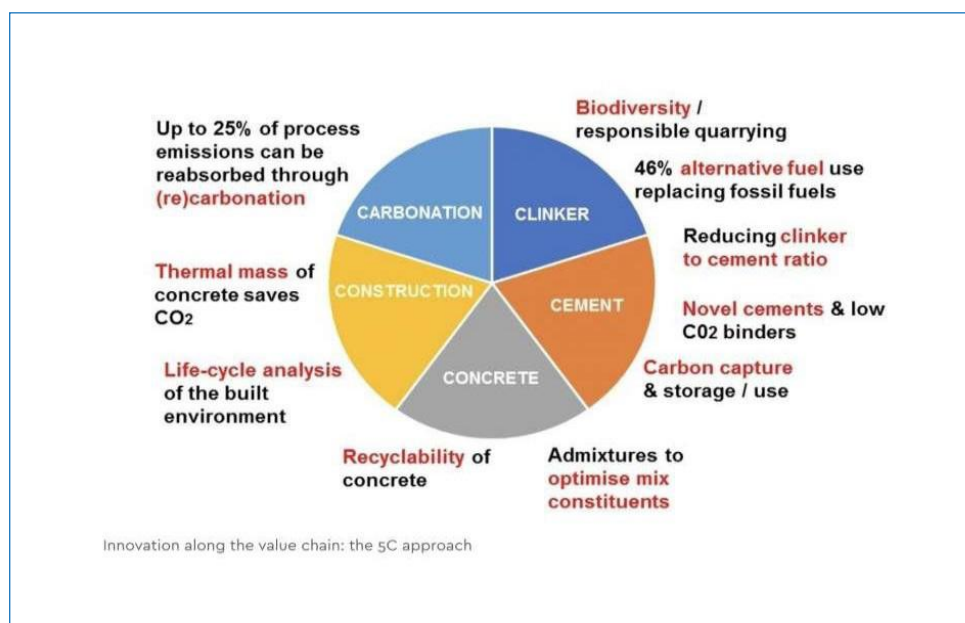


Fig. 15. Target pathway

### Is the implementation of low-carbon technologies helped by the government?

For refurbishing or replacing equipment? How are public authorities pushing the transformation? Through benchmarking? Audits?

The Bureau of Energy Efficiency's (BEE) Perform, Achieve, Trade (PAT) Cycle -1 (2012-15) included 478 units (Designated Consumers or DCs) from eight energy-intensive sectors, including cement. The minimum annual energy consumption of each DC was 30 000 tonnes of oil equivalent (toe). About 85 cement plants in India were notified as DCs under PAT I. As against a total saving target of 0.815 million toe (Mtoe), the sector achieved 1.48Mtoe of energy savings and 4.34 Mt of CO<sub>2</sub> savings.

The Confederation of Indian Industry (CII) is encouraging cement plants through its well-tested Energy Benchmarking Manual. The manual has been recognized as a useful tool for performance assessment, energy efficiency improvement and target setting across the industry to help cement plants achieve the status of efficient role model units. The CII has conducted its energy benchmarking study in 18 cement plants to date. These plants have realized a total energy saving potential of USD 19mn from the 516 energy-saving proposals identified during the energy benchmarking studies.

Other initiatives: The Bureau of Energy Efficiency (BEE) and the United Nations Industrial Development Organisation (UNIDO) have jointly created the Facility for Low Carbon Technology Deployment, a five-year programme that aims to promote innovative low-carbon technologies among industrial and other sectors of the Indian economy. The CII is working with the BEE and UNIDO to implement the programme, under which annual "innovation challenges" are being conducted to identify innovative technologies and solutions to improve efficient end use of energy and reduce greenhouse gas emissions.

### Are there incentives for carbon capture, utilisation, and storage? How?

The Department of Biotechnology (DBT) and Department of Science and Technology (DST), along with Accelerating CCUS Technologies (ACT) initiative under Mission Innovation (MI), has played an essential role in refocusing on CCS/CCUS in the Indian context by peer technology exchange and allocating funds for R&D.

The recently launched roadmap 2030 for India-UK future relations considers CCUS under clean energy and transport focus areas (MEA 2021). Thus, multiple initiatives highlight the resumption of the application of CCUS across industries in India.

Indian industries and public sector undertakings (PSUs) are leading the way towards the promotion of CCS facilities while recognising the need to stay carbon-neutral in the broader context of sustainability and competitiveness.

## If relevant, what about recycling?

**What percentage is recycled? What are the obstacles to increasing recycling? Is a policy to increase recycling already in place or at the project stage?**

At present, India recycles one per cent of its Construction and Demolition (C&D) waste. The Indian cement industry is contributing to the circular economy primarily by (i) Circular Supply Chain, (ii) Recovery and Recycling. Waste from various industries is being utilized by the cement industry as Alternative Fuels and Raw materials (AFR).

Besides C&D waste, recovery of energy in the form of Biomass, Urban, Industrial and Agricultural Waste, Refuse Derived Fuel (RDF) from Municipal Solid Waste (MSW) and used tyres for meeting captive power and thermal needs of cement plants. India generates over 150,000 tonnes of municipal solid waste per day, 8-9% of which contains plastics. It needs segregation and motivation with the objective of using various technologies at various stages including artificial intelligence.

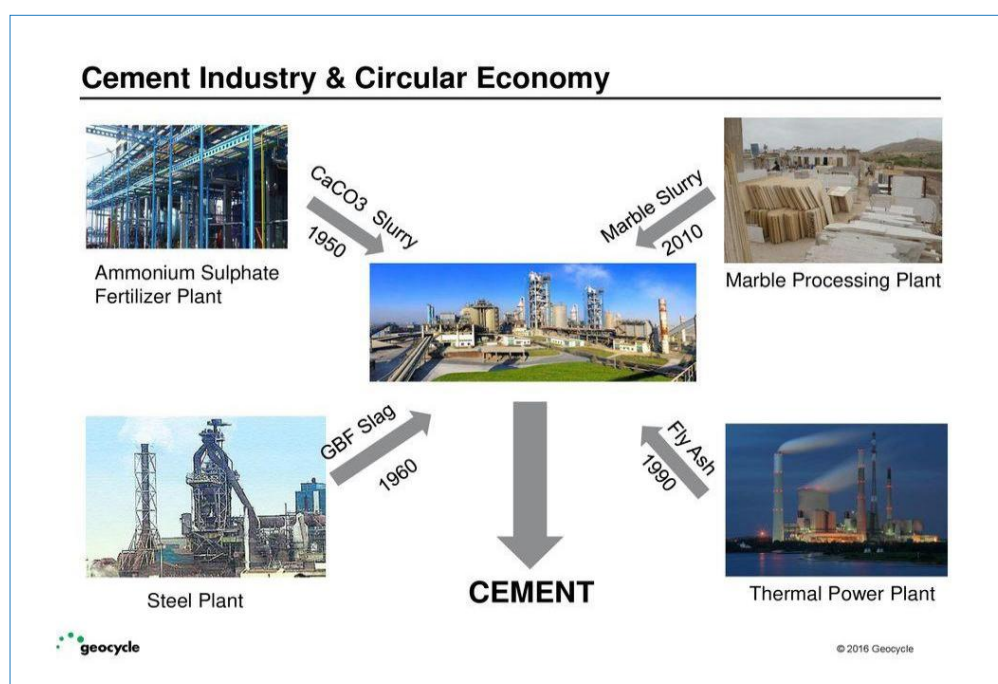


Fig. 16. Cement Industry & Circular Economy

Co-processing puts the cement industry at the heart of the circular economy and plays a key role in terms of waste management in local areas and municipalities and  $\text{CO}_2$  is saved by replacing fossil fuels.

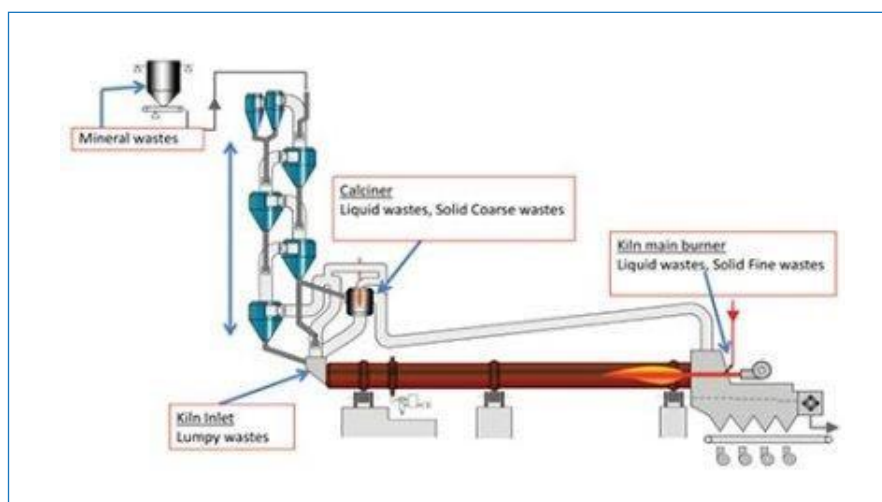


Fig. 17. Cement Kiln coprocessing

Production of blended cement, composite cement, and utilising performance improvers in cement also support the circular economy. The use of fly ash, granule blast furnace slag (GBFS) in the production of blended cement types, i.e. Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC) is also beneficial for the conservation of natural resources, lowering the clinker factor in cement and reducing CO<sub>2</sub> emission along with environmental sustainability.

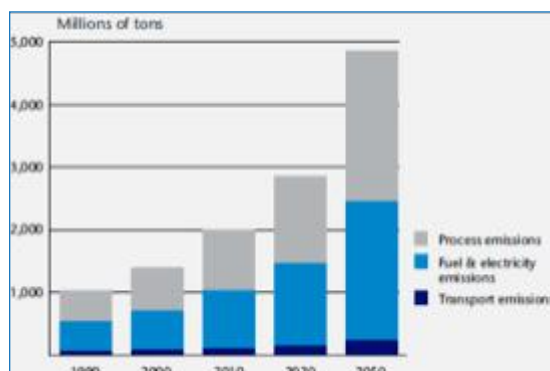


Fig. 18. Target - Coprocessing of Municipal solid waste

#### Barriers to the implementation of Recycling

- Limited involvement of government agencies/departments; lack of urgency.
- Transportation and segregation issues
- Lack of monitoring capacity/resources
- Lack of capacity and experience
- Lack of confidence in the quality and durability of recycled products
- Poor accountability framework

#### Are there some case studies or best practices you would like to share:

##### Case study 1

Indian industries are leading some of the largest projects exploring the role of CCUS, but more stakeholders and sponsors are needed to promote the adoption of CCS/CCUS technology for the transitional period to a green economy in India.

Dalmia Cement, in order to reach the level of  $-30 \text{ kgCO}_2/\text{ton}$  of cement by 2040, has announced the installation of a large-scale CCUS facility of capacity  $0.5 \text{ MtCO}_2$  per annum at one of its plants in Tamil Nadu, India. For the implementation of this facility, Dalmia Cement and Carbon Clean Solutions, UK, have come together to adopt the latter's patented technology, CDRMax (Global CCS Institute 2019).

The technology is far from becoming mainstream, but the Government of India and the Indian industry are trying to better understand the techno-economic feasibility and scalability of this technology.

Indian industries and public sector undertakings (PSUs) are leading the way towards the promotion of CCS facilities while recognising the need to stay carbon-neutral in the broader context of sustainability and competitiveness.

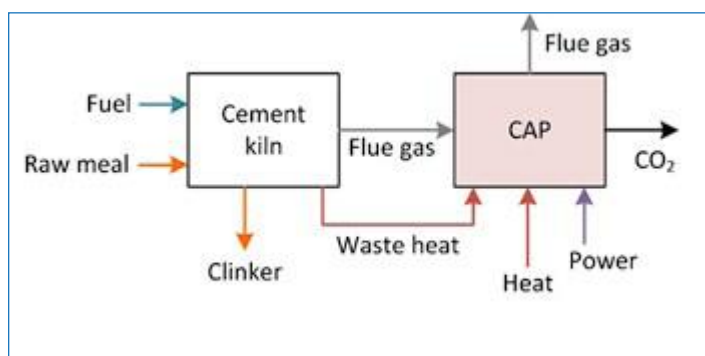


Fig. 19. The CAP Process for recovery of waste heat and capture and separation of flue gases, integrated into a cement plant

## Case study 2

Co-processing of plastic waste in cement kiln – ACC Ltd, Gagal Cement Works in Himachal Pradesh.

The project started with the collection of 50 kg of plastic waste per week. At present, it has reached the level of approximately two Tonnes of plastic waste collected per week. This gave a clear indication that the stakeholders were increasingly becoming more aware of the need for waste sorting and concerned about their environment.

The investment required for this project is very minimal as the method was already developed.

Co-processing of waste at a cement kiln is the best disposal option compared to conventional options, such as landfilling and incineration, with the benefit of substituting fossil fuels.

The initiative can be replicated countrywide by other cement factories, as well as at a global level. The beauty of the initiative is that by keeping the ideas intact, the projects can easily be adapted to suit the climate, topography and biodiversity of any area across India.

Besides, ACC Limited, Kymore Cement Works established the system and infrastructure for the co-processing of polythene garbage in its Kiln and the system is in operation since June 2008.

## Case study 3

A Waste Heat Recovery System was installed in 3 kilns (kiln capacity 4 300, 5 000 and 5 000 for kiln 1, 2 and 3 respectively) at JK Lakshmi Cement Ltd. Rajasthan (Sirohi) plant with a total capacity of 12 MW. Sources of heat for boilers are exhaust gases from the preheater and cooler of kiln-1, 2 and 3. It was not feasible to install an AQC boiler because waste gases from kiln 3 cooler are being used for the flyash drier.

## South-Africa

The South African Cement industry mainly consists of 6 large cement manufacturing companies with a combined production capacity of approximately 22 million tonnes of cement per year but currently only producing around 13 million tonnes. The industry is well regulated, with very strict Labour Laws, Mining Laws, Transformation requirements, compulsory National Standards adopted from European standards and Carbon Taxes. The industry is severely affected by cheap imports currently in excess of one million tonnes from countries with no labour laws, standards for quality assurance, environmental legislation or carbon taxes.

### What is the energy balance (energy sources used)?

### And the GHG intensity, compared to other countries?

Vosloo and Mathews (2017) estimated that about 88% of the energy supplied to cement plants comes from coal, with the remaining 12% coming from electricity. Due to the relative price difference, coal makes up only 61% of the energy cost, with electricity making up the remaining 39%. Electrical efficiency is thus a priority and large manufacturers have started retrofitting and recapitalizing heating and grinding processes in their plants.

The abundance of locally available coal makes it the most cost-effective source of energy. Alternative sources of energy, such as waste tires, are used in a couple of cement kilns, but constant and reliable streams of waste materials fit for generating heat efficiently remain problematic.

In South Africa, electricity is mainly generated in coal-fired power stations, producing large volumes of fly ash that is used to reduce the clinker content of manufactured cement. It is estimated that the South African cement industry managed to reduce the CO<sub>2</sub> emitted per ton of manufactured cement from 783 kgCO<sub>2</sub>/t cement in 1999 to 665 kgCO<sub>2</sub>/t in 2015. This value is slightly above the 2020 average international value as indicated by the GNR indicator<sup>1</sup>.

In 2010 the South African Concrete Institute commissioned a study on GHG emissions indicating the benefits of using blended cements as shown in *Table 1*. These values confirm that it would be possible to further reduce the GHG emissions by reducing the clinker content of South African cements, as indicated by the Ordinary Portland Cement (OPC) content in the table below.

Cement type	Composition (%)				Total GHG emissions (kgCO <sub>2</sub> /ton)
	OPC	Fly ash	GBBS*	Limestone	
CEM I	100	0	0	0	985
CEM II A-L	85	0	0	15	839
CEM II A-S	80	0	20	0	814
CEM II A-V	80	20	0	0	789
CEM II B-L	73	0	0	27	722
CEM II B-S	70	0	30	0	728
CEM II B-V	70	30	0	0	690
CEM III A	50	0	50	0	557
CEM IV A	65	35	0	0	641
CEM IV B	58	42	0	0	572
CEM V A	57	18	25	0	594
CEM V B	38	31	31	0	414

*Table 1.* GHG in kgCO<sub>2</sub>/ton per type of South African cement (InEnergy, 2010).

\* Ground Granulated Blast-furnace Slag

<sup>1</sup> Getting the Numbers Right (GNR) is an independently managed database of CO<sub>2</sub> and energy performance information on the global cement industry.

## **Are the best available low-carbon technologies used/considered?**

### **If not, is it an economic problem? A matter of regulation? Or some social issues?**

Where possible, the local cement manufacturers use the most appropriate low-carbon technologies such as electricity efficiency, thermal efficiency, alternative fuels, and reduction of the clinker-to-cement ratio. Although the modernisation of plants is considered, current economic conditions make this difficult. As more than 30 million tons of fly ash is produced annually by the coal-fired power plants in South Africa, reducing the clinker content of cement via an increase of fly ash, is the most obvious way of reducing the carbon footprint.

## **Is there a roadmap to decrease GHG emissions for 2030 - 2050**

### **If yes, what are the intermediary steps?**

Local manufacturers are increasingly manufacturing blended cements containing larger percentages of limestone, fly ash and Ground Granulated Blast-Furnace Slag (GGBS). In 1990, clinker substitution reached a level of 12% and this increased to 23% in 2000 and 41% in 2009. It is estimated that the clinker replacement level in South Africa would reach 60% by 2030. The nearly unlimited volume of high-quality fly ash available in South Africa will ensure availability for use at high clinker replacement levels until 2050 and beyond. South Africa is in the process of adopting EN 197-5 which allows for further extension of types of cement.

## **Is the implementation of low-carbon technologies helped by the government?**

Carbon taxes have been implemented and currently, negotiations are taking place to finalise the second round of Carbon taxes. Unfair competition from cheap unregulated cement imports remains a major stumbling block limiting the ability of local cement manufacturers to reduce GHG emissions while retaining their market share.

The South African National Accreditation System (SANAS) launched a programme for the accreditation of GHG validation and verification bodies for GHG quantification against the requirements of ISO 14065 that can be used in mandatory GHG reporting and evaluation of the implications of a carbon tax.

In October 2021 the South African National Treasury issued a circular, indicating that the cement sector has been designated as a sector for local production and content, thus all cement types used in state-funded contracts, must now be manufactured using locally produced clinker and locally sourced secondary materials. This should protect the local cement industry to the extent that it would be affordable to consider plant modifications required to reduce GHG emissions.

### **If relevant, what about recycling?**

Although cement is not recycled and there are no mandatory policies in place, practices such as the reuse of wash water at concrete plants and recycling of old concrete and demolition waste are widely used.

## **Are there some case studies or best practices you would like to share?**

Cement is used as a constituent of concrete and the carbon footprint of the cement and concrete industry can be minimized by optimizing the use of cement. Although concrete consists of about 70% fine and coarse aggregate, 20% water and 10% cement, the GHG emission of the concrete is dominantly that of the cement manufacturing process. It is thus important to not only limit the CO<sub>2</sub> emissions per kg of cement produced but also limit the kg cement used per m<sup>3</sup> of concrete. Although the production of water-reducing admixtures results in significant GHG emissions, small volumes of these admixtures can result in up to a 30% reduction in both water and cement content, reducing the carbon footprint of the resulting concrete. When considering the decarbonisation of energy end uses, it is thus important to not only focus on the cement production process but also on limiting the carbon footprint of the concrete produced and the infrastructure containing the concrete.

## Sweden

Cementa, which is part of the Heidelberg Cement group, is the only cement producer in Sweden with a capacity of approximately 3 Mt cement per year.

### What is the energy balance (energy sources used)? And the GHG intensity, compared to other countries?

Total energy around	4.0
Coal and coke	1.0
Waste (fossil origin)	1.8
Electricity	0.4
Biofuels	0.8

Table. 1. Energy sources for cement production in TWh/year

The Swedish cement industry emits around 2.5 Mt of CO<sub>2</sub> annually, equivalent to around 15% of the total industrial CO<sub>2</sub> emissions. The CO<sub>2</sub> emissions are both from the energy supply and in the form of process emissions (from the calcination process).

### Are the best available low-carbon technologies used/considered? If not, is it an economic problem? A matter of regulation? Or some social issues?

Within the framework of the Fossil Free Sweden initiative, a roadmap for carbon-neutral cement and concrete for the cement industry has been developed by Cementa.

Cementa works **towards a zero vision for carbon dioxide emissions** during the life cycle of concrete products. The target is to achieve climate-neutral construction with cement and concrete in 2030 as illustrated in *Fig. 1*, where the dark green area represents the remaining CO<sub>2</sub> emissions after reduction due to the elements described in the list below and represented by lighter shades.

Efforts to reduce emissions are being driven in five main areas in steps as shown in *Fig. 1*:

- energy efficiency
- decarbonisation by increasing the share of bio-based fuels
- development of new cement products with a smaller carbon footprint
- research into increased carbon dioxide uptake of existing concrete structures
- carbon capture followed by reuse or geological storage, which in the long term means a return to rock minerals

Investments have made it possible to replace more than half of coal in production with alternative and bio-based fuels.

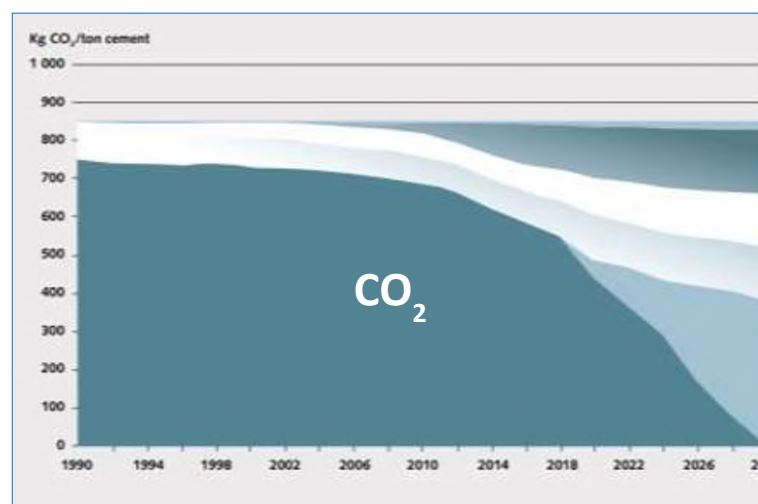


Fig. 1. Cement Roadmap

Source Cementa roadmap: [fardplan\\_cement-for\\_klimatneutralt\\_betongbyggande-20180424 \(3\).pdf](https://www.cementa.se/mediasida/attach_data/attachment_data/file/20180424/3.pdf)

Cementa has a plan to apply CCS to capture basically all CO<sub>2</sub> emissions from their largest plant (in Slite, Gotland) by Year 2030. Since they are also using renewable fuels, this may, depending on capture rate and the share of renewable fuels, results in net negative emissions from cement production: [Sweden first in the world with carbon-neutral cement plant | Cementa](#).

There are also possibilities to use alternative binders. The captured CO<sub>2</sub> will most likely be stored under the seabed in the North Sea as part of the Northern Light project.

(At the moment there are discussions on the permitting of continued cement production in Slite).

### Is there a roadmap to decrease GHG emissions for 2030 - 2050 If yes, what are the intermediary steps?

There are three roadmaps developed within the Fossil Free Sweden initiative which are relevant for the cement industry: The **cement roadmap** ([The cement industry - Fossilfritt Sverige](#)), the **Concrete roadmap** ([The concrete industry - Fossilfritt Sverige](#)) and the **roadmap for the building and construction industry** ([The construction and civil engineering sector - Fossilfritt Sverige](#))

The Swedish cement industry roadmap is targeting climate neutrality by 2030, with the main focus being on biofuels together with CCS.

All these have the aim to meet the Swedish target of net zero emissions by 2045.

### If relevant, what about recycling?

**What percentage is recycled? What are the obstacles to increasing recycling? Is a policy to increase recycling already in place or in project?**

Concrete is a fully recyclable material but handling and transport create financial thresholds for recycling in concrete production. Incentives are needed for a higher degree of recycling, including of whole concrete structures.

### Are there some case studies or best practices you would like to share?

Cementa, part of the Heidelberg group, is currently planning a large-scale implementation of CCS at their Norwegian sister factory (Norcem) in Brevik, Norway. Being part of the so-called Lanskip-project, which is linked to the Northern Light project, Norcem will capture around 400 ktCO<sub>2</sub>/year. <https://www.norcem.no/no/Press-MediaCCS>.

Together with Vattenfall, Cementa is also pursuing electrification through its CemZero project, with a pre-feasibility study released in 2018. Vattenfall and Cementa take the next step toward climate-neutral cement. Even with electrification or using biomass to abate the energy-related emissions, process emissions remain, and CCS still needs to be applied. However, the electrification serves to purify the flue gas streams which eases CO<sub>2</sub> capture.

# IRON AND STEEL INDUSTRY ANALYSIS

## Table of Contents

---

China .....	513
Korea.....	516
Sweden .....	519

## China

### What is the energy balance (energy sources used)?

### And the GHG-intensity, compared to other countries?

In China, the main production process in the Iron and Steel Industry is the Blast Furnace – Basic Oxygen Furnace (BF-BOF) process. Crude steel production accounts for more than 90% of total production in China in 2020.

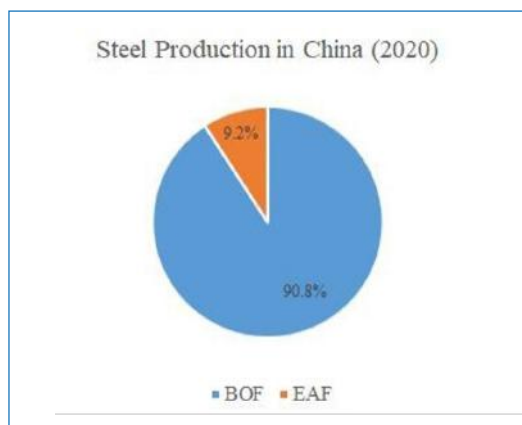


Fig. 1. Chinese Steel Production in 2020

In 2020, the energy consumption in the Iron and Steel Industry is about 16% of the total energy consumption in China. The use of coal for energy in this Industry accounts for more than 70% of the total, which causes high CO<sub>2</sub> emissions. For the BF-BOF process, the CO<sub>2</sub> emission is about 2 tonnes per tonne of steel. The total ironmaking process (including ironmaking per se, sintering, steelmaking, and rolling) produces 87% of CO<sub>2</sub> emissions in the overall process (see Fig. 2). For Electric Arc Furnace (EAF) process, the CO<sub>2</sub> emissions are about 0.35-0.5 tonnes per tonne of steel.

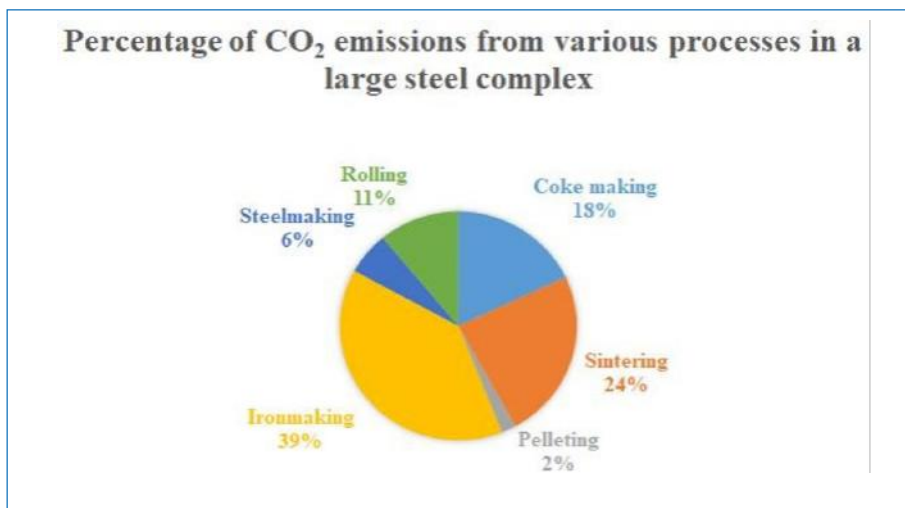


Fig. 2. CO<sub>2</sub> emissions from different processes in a large steel plant

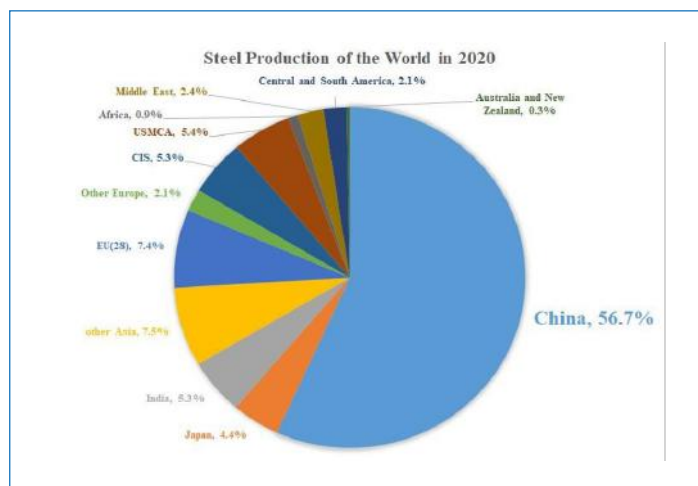


Fig. 3. Global Steel Production 2020

In 2020, the crude steel production in China is 1.065 billion tons, around 56.7% of the global production.

### Are the best available low-carbon technologies used/considered?

The energy-saving and emission-reduction technologies have been widely applied in large and medium-sized Iron and Steel enterprises in China with the development of a modern Industry. Some technologies, such as coke dry quenching, coal moisture control, waste heat recovery from the sintering process, electricity generation with residual pressure of top gas of blast furnace, etc., are state-of-the-art technologies in the world and are encouraged to be applied in the whole Iron and Steel Industry.

Further developments in emission-decreasing technologies have been conducted, such as hydrogen-rich iron-making in BF, oxygen-rich ironmaking in BF, using tail gas of steel plants as carbon resources to produce ethanol by connecting steel and chemical industry, hydrogen metallurgy, etc. EAF process can decrease 2/3 of the CO<sub>2</sub> emission compared with BF-BOF process, which is considered as an effective way in the future.

### Is there a roadmap to decrease GHG emissions for 2030 - 2050

#### If yes, what are the intermediary steps?

The Steel Association and the steel companies in China are making plans for peak carbon emissions recently. According to the primary planning, it is expected that the iron and steel industry will peak carbon emissions by around 2024, and carbon emissions from the steel industry in 2030 will be reduced by 30% compared with 2020.

### Is the implementation of low-carbon technologies helped by the government?

The Chinese government, including the national government and provincial governments, are supportive of the implementation of low-carbon technologies, such as the application of energy-saving, emission-reduction and new technologies in the steel industry.

The government has developed assessment methods for CO<sub>2</sub> emissions for steel manufacturers, which provide motivation for promoting carbon emission reduction in production enterprises.

### Are there incentives for carbon capture, utilisation, and storage? How?

China is now developing technology incentive policies.

### If relevant, what about recycling?

The EAF process is considered one of the important ways to reduce CO<sub>2</sub> emissions in the steel industry. For the EAF process, the feedstock could be steel scrap, which means the recycling of steel will become rather important. The increase in the steel scrap ratio in the BOF process could also reduce CO<sub>2</sub> emissions. It is planned that the utilisation of steel scrap as feedstock will be increased to 30% by 2025, and the ratio of EAF process in the steel industry will be enhanced to 15%-20% by then.

The relatively high cost of steel scrap and electricity, and the low amount of available steel scrap have so far limited the development of the EAF process in China. But this situation may change in the future.

**Are there some case studies or best practices you would like to share?**

Hydrogen metallurgy is an ideal green metallurgical process. At present, China has carried out in-depth research in hydrogen metallurgy technologies. In January 2019, CNNC, Baosteel and Tsinghua University have signed a cooperation framework agreement on the research of hydrogen utilisation in metallurgy. In November 2019, the Hegang group established the hydrogen energy technology and industrial innovation centre, cooperated with the Italian Tenova group in hydrogen metallurgy technology, and is planning to construct one of the world's first hydrogen metallurgy demonstration projects with a capacity of 1.2 million tons steel.

# Korea

## Which energy vectors are currently used for the processes in question (electricity, fossil fuels, bioenergy, etc.)?

In 2019 Korean Steel production was approximately 71 MT, which was 6<sup>th</sup> overall globally. The apparent steel use per capita in 2019 was 1 039 kg, which ranked 1<sup>st</sup> globally. The ratio of the domestic steel production between the integrated steel route (BF-BOF) and the electric arc furnace route was approximately 70% (49.7 MT) to 30% (21.3MT), respectively. The energy consumption of the integrated steel route and the EAF steel route is given below.

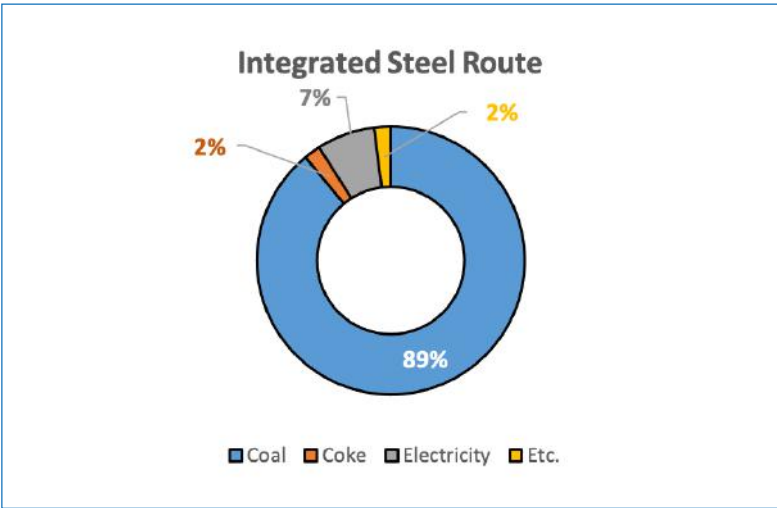


Fig. 1. Integrated Steel Route: Energy consumption in %

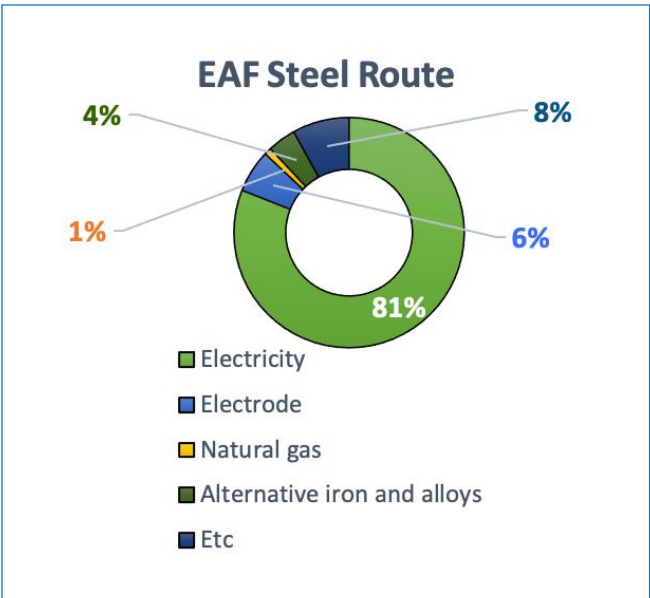


Fig. 2. Electric arc furnace: Energy and Alternative iron and alloys (e.g. scrap iron and steel) in %

As can be seen, the use of carbon-based reductants accounts for more than 91% of the total energy use (10.43 GJ) in the integrated steel route, which is approximately 9.4 GJ/t. Bioenergy or so-called carbon-neutral energy sources are not actively incorporated into the steel manufacturing processes in Korea. There have been commercial scale trials within specific BF and EAF operations, but these resources are not generally used, yet.

## How dependent is the decarbonisation of the industry on the energy- and electricity mix of the respective countries or regions and on current regulations?

Currently being assessed.

## Which are the principal elements of the value chain?

(the economy of the industry, including costs).

Currently being assessed.

## Is recycling of scrap metal already a major factor in iron and steel production and what about the availability of the needed quantities of scrap metal in different countries?

Scrap availability and consumption in Korea is provided in the Table below.

Division	'14	'15	'16	'17	'18	'19
Domestic scrap	24 065	23 359	21 604	24 205	23 841	22 920
Imported scrap	8 000	5 750	5 850	6 160	6 450	6 500
Supply	32 065	29 109	27 454	30 365	30 291	29 420
Self sufficiency	75.1%	80.2%	78.7%	79.7%	78.7%	77.9%

Table 1. Scrap supply for the Korean steel industry (Units: kt)

Division		'14	'15	'16	'17	'18	'19
Imports	Japan	3 830	3 130	3 420	4 000	4 040	4 018
	%	47.9	54.4	58.5	64.9	62.6	61.8
	US	1 640	970	890	520	870	1 108
	%	20.5	16.9	15.2	8.4	13.5	17.0
	Russia	970	880	1 030	1 020	930	712
	%	12.1	15.3	17.6	16.6	14.4	11.0
	Others	1 560	770	510	620	610	662
	%	19.5	13.4	8.7	10.1	9.5	10.2

Table 2. Major scrap import countries into Korea (Units: kt)

Social network analysis of the scrap trade indicates most of the scrap to be from Japan, the US, and Russia. Considering the logistics and costs associated with the scrap trade, diversification of the import countries is not likely but could be an option if the costs are competitive. Consumption of scrap is expected to increase, considering the near-term goals for CO<sub>2</sub> emissions control. The integrated steelmakers expect to increase the scrap utilisation in the hot metal ratio to above 25% from its current level of approximately 18% in the near term (2025). Assuming that the production is constant at approximately 49.7 MT, the integrated steelmakers will need approximately 3.5 MT of additional scrap to meet demand. However, at current cost levels, demand for high-quality scrap could exceed supply. Scrap suppliers could supply higher quality scrap in sufficient quantities, but this would require additional handling, increasing costs. Removal of tramp elements such as Cu, Sn, Zn, and others is costly, but the steel producers may not be willing to assume the costs of the higher quality scrap, even though this would be necessary in order to produce the required high-quality flat products.

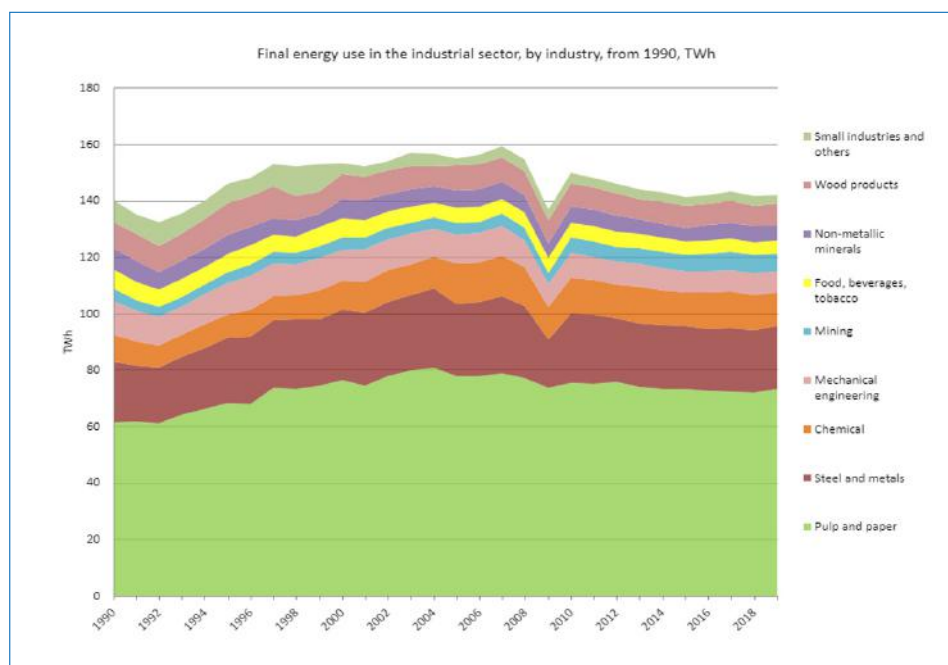
According to recent publications on the expected scrap supply and quality, Cu will especially be a problem element that needs to be addressed since there will be an eventual accumulation of this element in the scrap supply lowering the quality of scrap. Current refining technologies are still inadequate to remove this element from scrap steel and therefore it is usually diluted. However, greater utilisation of scrap will inevitably increase the Cu content in steel and ways need to be found to remove it prior to the steelmaking operations. EAF steelmakers typically producing long products will also need to integrate more high-quality scrap from the integrated steelmakers in order to be in a position to dilute the low quality scrap.

Considering the costs and availability of scrap and other necessary products, there will likely be an increase in the utilisation of direct reduced iron. Depending on the cost ratios and the operational efficiency, it is expected that overall a 10% scrap mix should be possible in the current state of operations.

**Remarks:** The sustainability of the steel industry in general requires collaboration between the respective parties. Hydrogen production using renewable energy sources needs to be readily available to the global community at a reasonable price. Developing countries should be in a position to use sustainable energy sources at lower costs than the already developed countries and ensure that the hydrogen-based steel route is widely accepted in those developing countries with the most urgent need for decarbonised steelmaking. It is imperative that these countries with sustainable energy resources attempt to provide the global community with cost-effective and green hydrogen.

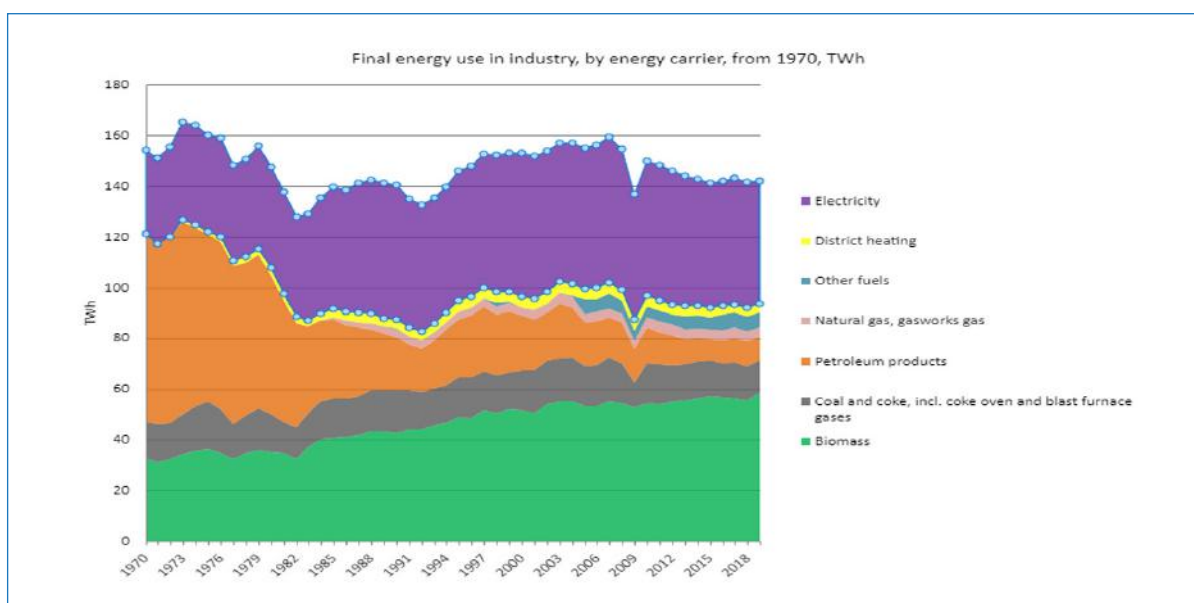
## Sweden

**What is the energy balance (energy sources used)?  
And the GHG-intensity, compared to other countries?**



**Fig. 1.** Total final energy use in the industrial sector, by industry, 1990 -2019

Three industries account for a large share of energy use. The pulp and paper industry, iron, steel and metalworks, and the chemical industry together accounted for around 75 percent of the industrial sector's final energy consumption in 2019. The engineering industry and the timber industry accounted for a good five per cent each of final energy consumption and other industries accounted for 14 per cent. Other industries include the mining industry, the food industry, the textile industry, the graphic industry, the agricultural and stone industries (manufacture of glass, cement and lime), as well as those industries that are usually classified as smaller industries.



**Fig. 2.** Total final energy use in industry, by fuel type and other energy vectors

The pulp and paper industry accounts for more than half of the final energy use within the industrial sector. Mainly biofuels and electricity are used in pulp and paper industrial processes. The use of fossil fuels; such as natural gas, petroleum products, coal and coke; is decreasing. However, their use is still extensive, especially within the iron- and steel industry.

- **Steel industry** (except mining) energy consumption: 22 TWh in 2019

The energy used are:

Coal incl Coke gas	11.4
Electricity	7.5
Gas	2.6
Oil	0.5

Total emissions in 2019 from the steel industry in Sweden are 6 MT of CO<sub>2e</sub>, representing 12% of total GHG emissions in Sweden. 85% of that is due to the reduction process of iron ore to iron, mainly in blast furnaces. 12% is from fuels for heating and heat treatment and 3% from raw materials and others.

- **Mining industry** (except cement industry)

Energy uses around 6 TWh, mostly electricity

Total CO<sub>2</sub> emissions in 2019 from the mining industry (excluding the cement industry) in Sweden: 1 MT

### Are the best available low-carbon technologies used/considered?

Swedish steel industries have highly efficient production processes, and the current best available techniques are used. Swedish steel products have an internationally low climate footprint. But still mainly based on blast furnaces with coal. A high degree of electrification, for example using electric arc processes, means lower life cycle emissions, and specialised products will entail increased resource efficiency when they are used.

### Is there a roadmap to decrease GHG emissions for 2030 - 2050

#### If yes, what are the intermediary steps?

Yes, it is the Climate Roadmap for a fossil-free steel industry ([climate-roadmap---summery.pdf \(jernkontoret.se\)](#))

The Swedish steel industry presented a vision for 2050; "Steel shapes a better future", with the purpose that we shall have a fossil-free and competitive steel industry in Sweden in 2050.

The most important potential solutions today are:

- The development of brand-new process technologies which apply hydrogen to reduce iron ore to iron instead of using coal and coke in traditional blast furnaces (the Hybrit and H2 Green steel projects). The technology requires a large amount of fossil-free electricity. The idea is that this will to a large extent come from wind power combined with hydrogen storage to avoid high-cost periods of electricity. Yet, a large share of the Swedish electricity mix will be from hydropower and nuclear power.

At the current level of production, the technique implies an increased need for about 15 TWh of electricity. Decided plans for a new green steel production facility mean another increase of 12-25 TWh of electricity around 2030.

- The development of biocoke for the reduction of iron ore for powder production and for scrap melting processes. This requires access to biomass for biocoke at a comparative cost.
- Electrification of heating and heat-treatment processes. This is mainly possible for heating at temperatures below 1 000°C.
- The use of bio-based gas or hydrogen as a substitute for the fossil fuels used in heating and heat-treatment processes where electrification is not an alternative. This requires access to a fossil-free gas of equivalent quality as natural gas and liquefied petroleum gas. The estimated need is at least 2-3 TWh at the current level of production.

Conditions for success

- Funding for long-term research and knowledge development
- Secure supply of fossil-free electricity to competitive costs
- Electricity is an enabler, increased needs in the future

- Development of an increased supply of biobased fuels and biochar
- More efficient permit processes for investment in new technologies
- Holistic view in the political arena with the aim for industrial growth

## Mining Industry

The roadmap for a competitive fossil-free mining and minerals industry in Sweden ([fossilrapport-2019-sammanfattning-eng.pdf](#)) is currently under revision and a new version will be published in late 2021.

One of the most important ways to achieve fossil-free operations is via electrification.

Supported by biofuels where electricity cannot be used. Machines and transportation within mining operations can be fossil-free by 2035.

Further automation and digitalisation will reduce energy needs and result in a more efficient and optimized vehicle fleet.

A fossil-free mining and metals sector will need to use more electricity and bioenergy than it does today. As a complement to the roadmap development, a rough estimate of these requirements has been attempted and is now also updated during 2021. Compared to today the industry's new estimates (to be published in late 2021) are that a fossil-free sector in 2045 would require around 70 TWh of electricity and around 3 TWh of bioenergy.

The most important factors where the public sector can make a difference are:

- Effective and fair permitting processes so that new and necessary, climate-efficient investments can be made possible.
- A holistic approach to political decision-making that avoids suboptimal instruments that weaken competitiveness and make fossil-free operations more difficult
- Investments in research and development for fossil-free production processes and CCS, including test and demonstration facilities
- Conditions that facilitate access to fossil-free electricity at a low total system cost and high reliability.
- Access to bioenergy at a competitive price

## Fossil-free electricity is the key enabler to the decarbonization of the steel, mining and iron and industry.

The total use of electricity in Sweden has been almost constant for more than 30 years, around 140 TWh. But now a dramatic increase is expected. Many studies of expected electricity needs have been made by different stakeholders. The outcome differs but all of them indicate a strong increase in the next 20-30 years.

The decarbonisation of the steel and mining industry assumes lots of hydrogen through electrolysis with fossil-free electricity and increased electrification processes. The steel and mining industry alone expects in total an **increased demand around the year 2045 of between 60 – 100 TWh** electricity depending on high-level min or max scenario.

## Is the implementation of low-carbon technologies helped by the government?

The Swedish Energy Agency is financially supporting new technologies in the industry through the programme Industrial Leap. [Flying start for the first investment in a new industry venture \(The Industrial Leap\) \(energimyndigheten.se\)](#)

The programme has supported the construction of a pilot plant for fossil-free steel production (the HYBRIT project) that was ready in 2020. The support from the Swedish Energy Agency covers 25 per cent of the cost for the actual pilot plant, and higher percentages of the different scientific projects.

The Swedish Energy Agency is also supporting the construction of a high-pressure underground lined cavern for the storage of fossil-free hydrogen.

Yet, since several automotive manufacturers have targets of climate neutrality, they need climate-neutral steel. Thus, it seems likely that both Hybrit and H2 Green steel will have customers for their climate-neutral steel once it is available. This is promising since economic sustainability obviously requires that the customers (rather than the governments) pay for climate-neutral products in the long run. Also, the additional price required

on end products (e.g. a car) for climate-neutral steel should be less than 0.5%.

The budget bill 2022 includes a proposal for economic support for biogas production.

### **Are there incentives for carbon capture, utilisation, and storage? How?**

There are no general incentives for investments outside of public financing of research and education at universities.

### **If relevant, what about recycling?**

Metals are 100% recyclable. There is a well-functioning market for metal scrap and for well-established technologies to use recycled metal in the production of new products. Policies concerning recycling need to be adapted to different material characteristics. For metals, there is no need for policy measures.

### **Are there some case studies or best practices you would like to share?**

In Sweden, more than one billion SEK (about 105 million Euros) is invested each year in steel research. A major part of this research is carried out within the different steel companies.

Three important and world-leading projects are on the way:

**HYBRIT** (Hydrogen Breakthrough Ironmaking Technology) is set up to develop a fossil-free value chain for iron and steel production using fossil-free electricity and hydrogen for direct reduction with the aim of replacing traditional blast furnace-based technology. The goal is a unique value chain, from mine to fossil-free steel. ([Hybrit \(hybritdevelopment.se\)](https://hybritdevelopment.se))

**H2greenSteel** will be a fully integrated greenfield fossil-free steel plant with the aim of bringing emissions down to zero. The technology is more or less the same as HYBRIT: direct reduction with hydrogen and electric arc furnace.

([H2 Green Steel](#))

**Höganäs AB** is the world's first plant for demonstrating, on an industrial scale, fossil-free steel metal powder production based on the gasification of biomass by using new technologies. The plant gasifies biomass to energy gas which will replace natural gas in Höganäs AB's metal powder production. Cortus Energy's unique gasifying process Woodroll® is gasifying the biomass.

([Unique plant for renewable energy gas and bio-coke | Höganäs \(hoganas.com\)](#))

**Ovako** is initiating the construction of a fossil-free hydrogen production facility to be used as a fuel in heating processes. Cooperation with the transport sector will make hydrogen also available for fuel-cell trucks.

([First in the world to heat steel using hydrogen - Ovako](#))

**LKAB** is Europe's leading mining and minerals group, wholly owned by the Swedish State. LKAB's strategy paves the way for zero carbon dioxide emissions from their own processes and products by the year 2045 and secures the company's operations beyond the year 2060.

LKAB is facing the biggest transformation in the company's 130-year history, which could become the biggest industrial investment ever in Sweden. The strategy creates unique possibilities for LKAB and the Swedish industry to take the lead in a necessary conversion.

The strategy consists of changes in three major areas:

- New world standard for mining. Through digitalisation, automation, electrification, new operation methods and carbon dioxide-free production we will set a new world standard for mining.
- Carbon dioxide-free sponge iron with hydrogen technology. Through the shift from iron ore pellets to carbon dioxide-free sponge iron LKAB will take an important step forward in the value chain, increasing the value of its products while giving the customers direct access to carbon dioxide-free iron for steel production.
- Extract critical minerals from mine waste. Using fossil-free technology LKAB will extract strategically important minerals and phosphorus for mineral fertilizers from today's mine waste.

<https://www.lkab.com/en/about-lkab/lkab-in-brief/strategy-and-goals/>

**Sustainable Underground Mining project (SUM)** is a test bed project for an integrated, efficient and carbon-free mining system. The goal is to implement carbon dioxide-free and autonomous mining in a physical as well as virtual test mine, and then scale up and introduce the mining methods in LKAB's underground mines in Kiruna and Malmberget. The project has financial support from the Swedish Energy Agency.

[SUM industrial collaboration strengthened with the addition of a new partner \(lkab.com\)](#)

**ReeMAP Industrial Park** is to become a centre for the chemical engineering industry in northern Sweden which extracts tomorrow's resources using innovative technology. During the processing of iron ore, by-products are created. These by-products, so-called tailings, are deposited in tailings ponds. These tailings sands contain valuable minerals such as phosphorus, rare earth elements and fluorine. In the ReeMAP project, LKAB wants to develop the technology that will allow us to utilize these minerals and convert waste into valuable resources.

[ReeMAP Industrial Park | LKAB Minerals | ReeMAP project \(ree-map.com\)](#)