CAETS ENERGY REPORT 2022

TOWARDS LOW-GHG EMISSIONS FROM ENERGY USE IN SELECTED SECTORS

CAETS
International Council of Academies of Engineering & Technological Sciences

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Annexes

The Annexes to this report will be accessible in a separate publication. They 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 level 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.

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EXECUTIVE SUMMARY

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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 (International Council of Academies of Engineering and Technological Sciences) Member Academies 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_2 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_2 content of less than 50 g per kWh over the life cycle of the installation. Low-carbon electricity is therefore mainly[1] produced by hydro, solar, wind and nuclear power.

As the different chapters of the report show, reducing GHG emissions, especially CO_2, 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_2 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_2 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.

[1] 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_2 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_2 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 $GtCO_2$ and around 2.5 $GtCO_{2e}$ from methane (CH_4).

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_2 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 $GtCO_2$) 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_2 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 $GtCO_2$). It is thus one of the largest CO_2-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_2 emissions from cement production are due to calcination, the chemical reaction liberating CO_2 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_2 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_2 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_2 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_2 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_2, representing around 8% of global anthropogenic CO_2 emissions.

Considering the urgency of the reduction of CO_2 emissions and the lifetime of many existing facilities, the Committee recommends implementing every possible and economically affordable, even marginal, reduction of CO_2 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_2 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_2 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_2 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 expansion 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_2 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.

CHAPTER 0. TO SET THE SCENE

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

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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_2, CH_4, N_2O, and SF_6, keep increasing as shown in *Fig. 0.1.* (in this figure, data for 2020 is only available for fossil CO_2 and Land Use, Land Use Change and Forestry (LULUCF), but not for Fluorinated Gases (F-gases), CH_4 or N_2O). The result is that in 2019, the annual avarage concentration of CO_2 in the atmosphere reach 410 ppm, compared to 280 before the industrial age (See IPPC - Climat change 2021 - The physical science basis - Summary for policymakers).

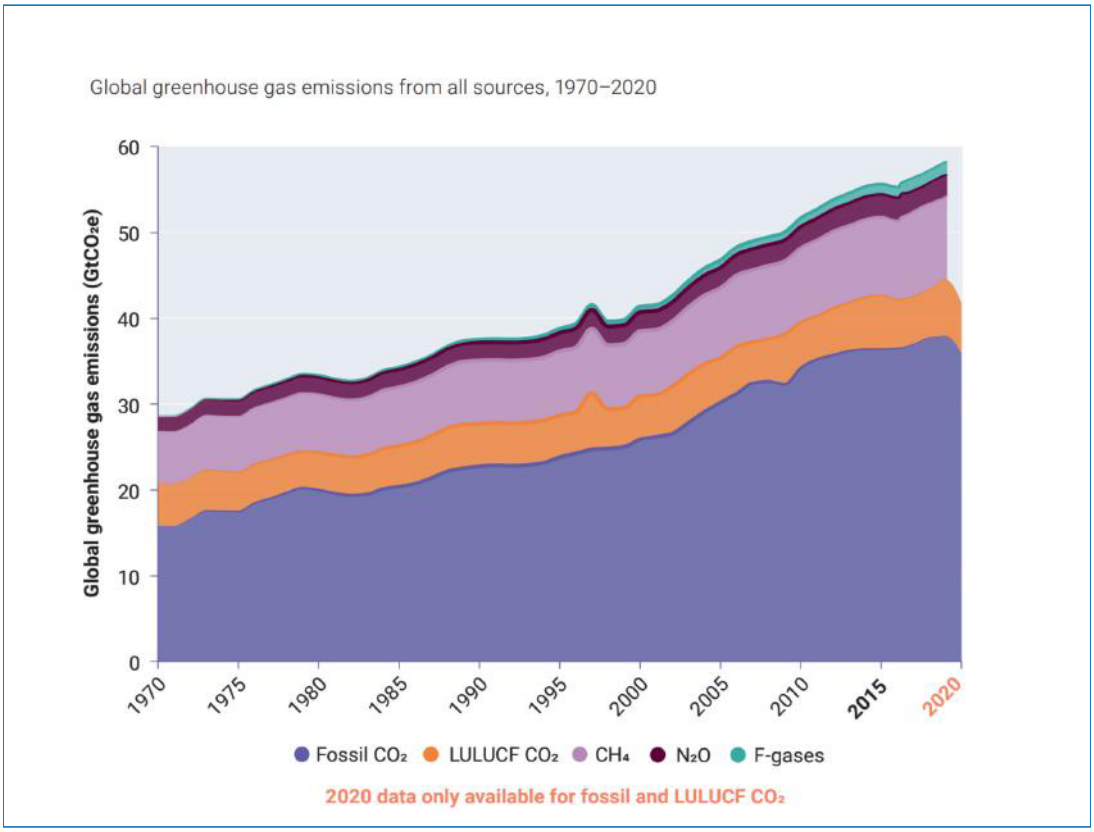

Fig. 0.1. Global GHG emissions from all sources
Source: Emissions Gap Report 2021: The Heat Is On, page XVII
https://www.unep.org/resources/emissions-gap-report-2021

The CAETS[1] 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

[1] 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[2], 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'[3] 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 emisssions 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

[2] https://www.newcaets.org/statements-reports/caets-reports
[3] 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).

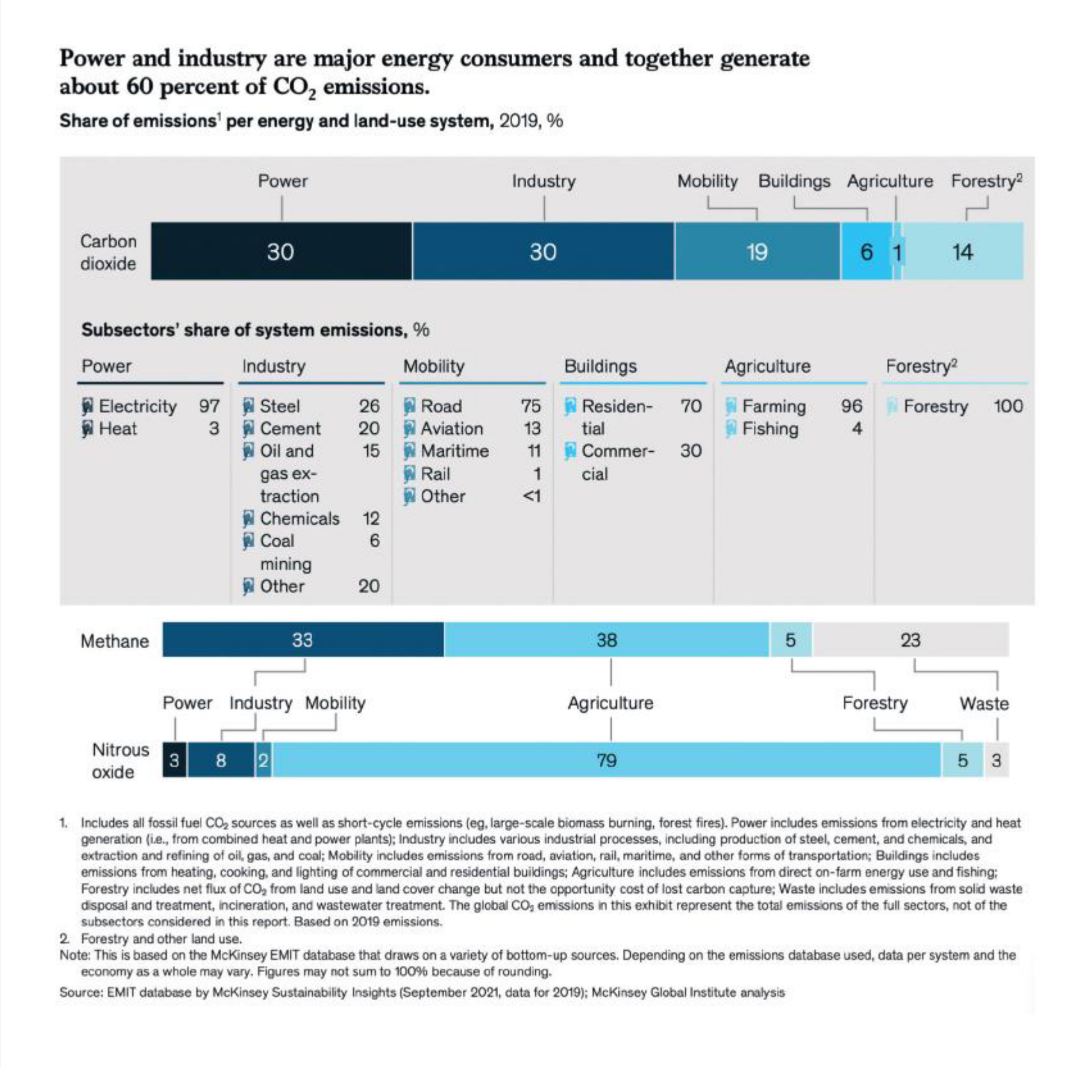

Fig. 0.2. Percentage of CO_2 emissions by sector, 2019
Exhibit from "The net-zero transition. What it would cost, what it could bring", January 2022, McKinsey & Company, www.mckinsey.com.

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[4], as defined in the studies on Climate Change[5]. 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 sumarises 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.

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[4] 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.

[5] See for example: 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_2 emissions. This is likely to happen at a different pace in each country.

What is low-carbon electricity?

The CO_2 content of electricity, also known as the CO_2 intensity of electricity, is usually characterised by the number of grams of CO_2 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_2 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_2 content is generally estimated to be between 10 gCO_2/kW and 50 gCO_2/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_2 content of electricity worldwide was:

- 950 gCO_2/kWh for coal, with plants below 900 gCO_2/kW and others at 1 100 gCO_2/kWh,
- 430 gCO_2/kWh for natural gas, with plants around 350 gCO_2/kW and others at 550 gCO_2/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_2/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 theses 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[6]: 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_2 emissions from electricity production must decrease. Per kilowatt-hour, indeed, this has been achieved since 1990, as shows *Fig. 0.3.*[7] below, dropping from 533 gCO_2/kWh to 485 gCO_2/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.

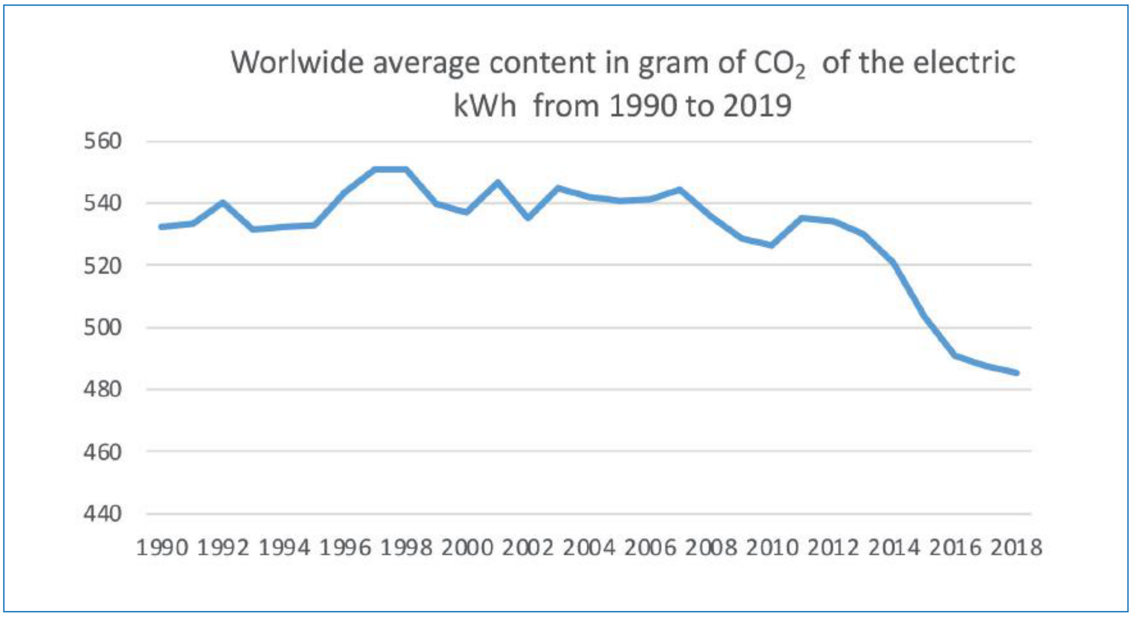

Fig. 0.3. Worldwide average CO_2 content of electricity 1990 to 2019 [CO2/kWh]
Source: IEA. Reproduced with permission
https://www.iea.org/data-and-statistics/data-product/emissions-factors-2021

For the last two options above, technologies are available but still need incentives, such as new regulations imposing higher prices for CO_2 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.

6 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/

7 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_2 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_2 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_2 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 forgeting 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_2 emissions: see for example *Chapter 6.* on the steel industry, and below.

Low primary energy and low CO_2 emissions are not necessarily synonymous

Let's suppose a country has the following electricity mix[8]:

50% renewables (hydro, solar, wind), 25% nuclear, 25% gas (with 50% efficiency, thus 400 gCO_2/kWh)
In that case, following the IAE coefficients (3 for nuclear), the ratio primary energy to final energy is given by Ep / Ef = [(50% x1)+(25% x 3)+(25% / 0,5)] / 100% = 1.75
The CO_2 content of electricity is: 25% x 400 = 100 gCO_2/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 $kgCO_2$.
- 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 x 1.75) and its emissions are (4 MWh/3) x 100 kg/MWh = 133 $kgCO_2$.

With this electricity mix, it is thus better to take directly CO_2 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 shutdowns for repear 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.

[8] Producing 1 kWh by combustion of gas produces some 200 g of CO_2. 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_2/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 (*See:* https://iea.blob.core.windows.net/assets/2867cfa4-5184-4d4e-801b-c545de7e8900/2.Mr.MasanaEZAWA%2CMETI17-03BenchmarkingWorkshop.pdf).

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 developped 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_2 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).

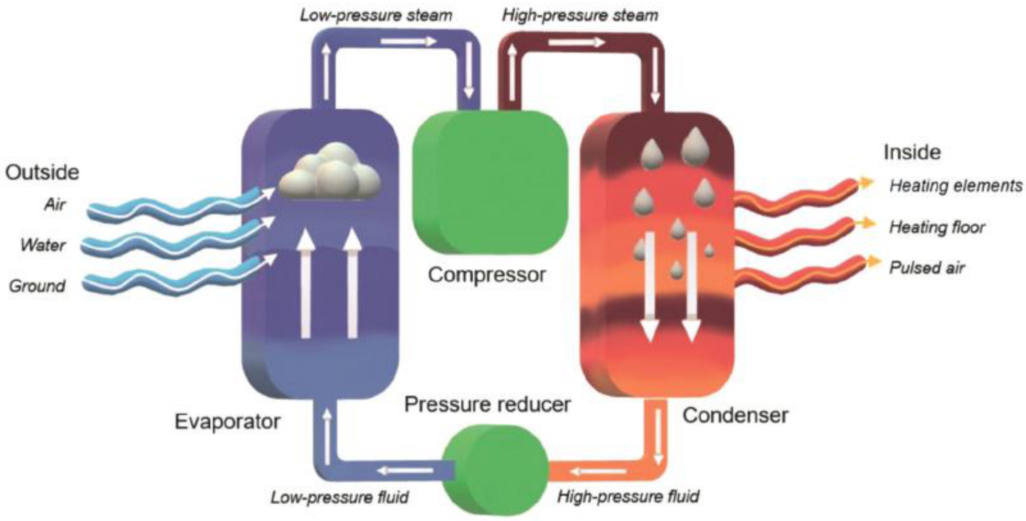

Fig. 0.4. Heat pump operating principle (© Püttgen-Bamberger) Reproduced with permission

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_2/kWh, the emissions from the heat pump system are lower, provided the electricity mix contains less than 600 gCO_2/kWh. This is the case in many regions since the average CO_2 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

Green: hydrogen produced by electrolysis of water, using electricity from renewable sources like hydropower, wind, and solar. Zero carbon emissions are produced	**Turquoise:** hydrogen produced by the thermal splitting of methane. Instead of CO_2, solid carbon is produced
Pink/purple/red: Hydrogen produced by electrolysis using nuclear power	**Black/gray:** hydrogen extracted from natural gas using steam-methane reforming
Yellow: hydrogen produced by electrolysis using grid electricity	**Blue:** gray or brown hydrogen with its CO_2 sequestered or repurposed
White: hydrogen produced as a byproduct of industrial processes (i.e. fracking)	**Brown:** 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_2 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_2 emissions associated with the production of gray hydrogen in the best-case scenario (D. Jakobsen & V. Åtland, 2016).

Process	CO_2 Emission (tonne CO_2 / tonne H_2)
SMR	8.5
POX	8.6
ATR	8.2

Table 0.2. CO_2 emission from H_2 production with natural gas for SMR, POX and ATR

To address the high CO_2 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_2 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_2 , compared to USD 1.0- 1.9/kgH_2 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)
Electrolyte	KOH/NaOH (liquid)	Polymer (solid)	Ceramic (solid)
Operating Pressure (bar)	2-10	15-30	<30
Operating Temperature (°C)	60-90 (up to 200)	50-90	500-1000
Stack Lifetime (h)	<90,000	<40,000	<40,000
System Lifetime (year)	20-30	10-20	-
Efficiency (HHV)	62-82%	67-84%	~90%
Cold Startup (min)	>15	<10	>60
Annual Degradation (%)	2-4	2-4	17
Cost at 2019 (US$/kW)	500–1400	800–1800	> 2800
Target Cost by 2050 ($/kW)	~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

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 electrolysers 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.*).

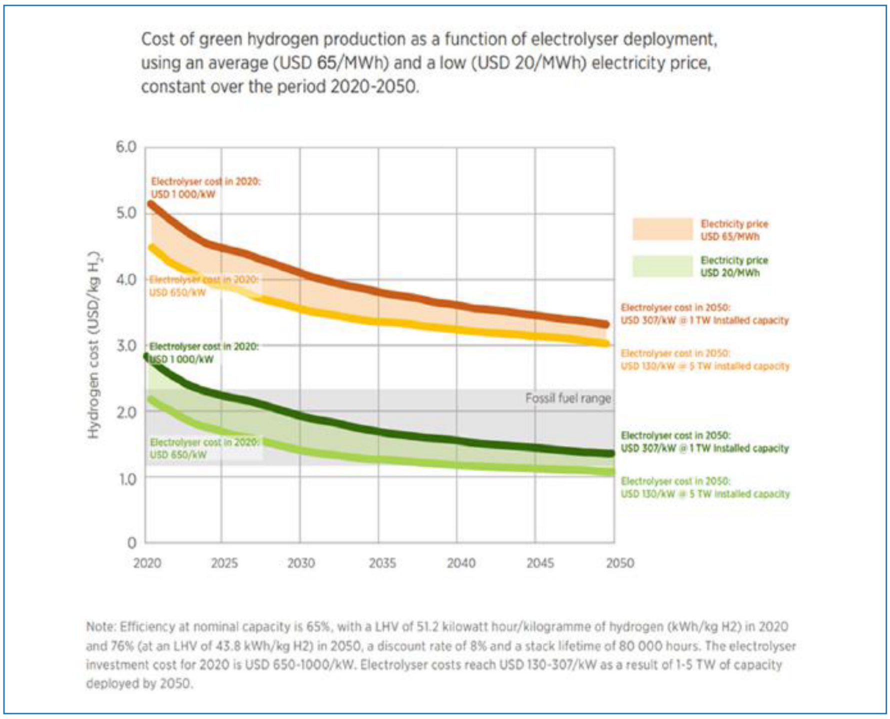

Fig. 0.5. Green hydrogen production costs projected by IRENA. © IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal,
International Renewable Energy Agency, Abu Dhabi.
https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

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
Enery 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[9] 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_2 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_2, methane, N_2O, etc. In many studies, these are combined and reported as global warming potential (GWP) in the form of CO_2-equivalents (CO_2e).
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.

[9] 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.

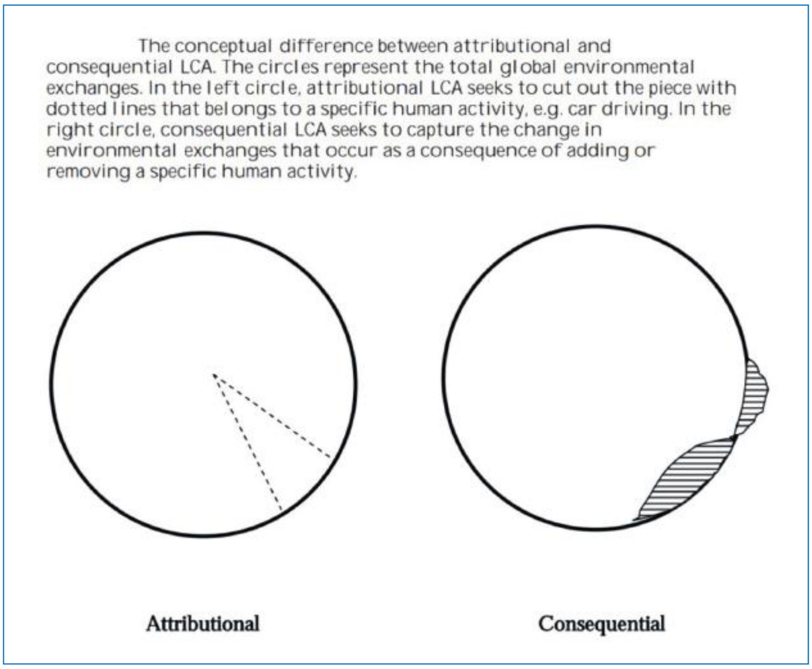

Fig. 0.6. The conceptual difference between Attributional and consequential LCAs (from Weidema BP. Market Information in Life Cycle Assessment. Environmental Project no. 863. Copenhagen: Danish Environmental Protection Agency; 2003. 147p. Page 15. https://www2.mst.dk/Udgiv/publications/2003/87-7972-991-6/pdf/87-7972-992-4.pdf)

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 Spheramodels[10].

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.

[10] 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

Pãtzay 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).

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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 20th and 21st 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)[1] 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 20th 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.

[1] 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 20th and 21st 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[2]. 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.

2 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_2 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.

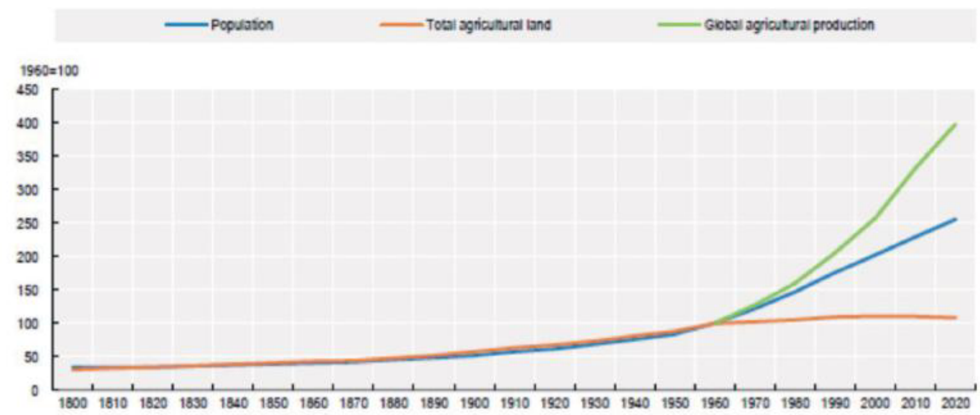
Since the 1960s and, just like other sectors of the economy, food supply underwent an agricultural revolution decoupling land use and production and relying on a carbonisation of food and agriculture systems that is well documented by many scholars. What is known as the modernisation of agriculture (or 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)[3]. 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[4].

3 Paillard, S., Treyer, S., & Dorin, B. (2014). Agrimonde–scenarios and challenges for feeding the world in 2050: Springer Science & Business Media.

4 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.



Source: Population data from Maddison's historical statistics for 1820-1940; UN Population Division for 1950-2010; 1800 and 1810 extrapolated from Maddison. Agricultural (crops and pasture) land data for 1800-2010 from the History Database of the Global Environment (HYDE 3.2), Klein Goldewijk et al. (2017). Global agricultural production data for 1960-2010 from FAOSTAT (Net Agricultural Production Index); data for 2020 from OECD/FAO (2020), "OECD-FAO Agricultural Outlook", OECD Agriculture statistics (database), http://dx.doi.org/10.1787/agr-outl-data-en.

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
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[5]. 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[6]. 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[7, 8]. 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[9, 10, 11].

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

6 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

7 Caron, P., Ferrero y de Loma-Osorio, 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

8 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

9 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

10 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.

11 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[1, 12]. This percentage can vary from 25% to 33% according to different reports. According to IPCC (2022)[1], 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_2 emissions, 38% of global methane emissions (CH_4, essentially related to ruminants' production), and 79% of global N_2O emissions (essentially related to rice production). Quantitatively, agricultural CH_4 and N_2O emissions are estimated to average 157 ± 47.1 $MtCH_4$/yr and 6.6 ± 4.0 MtN_2O/yr or 4.2 ± 1.3 and 1.8 ± 1.1 $GtCO_{2e}$/yr respectively between 2010 and 2019[1].
- 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[13].
- 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[11].

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)[14] 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)[15] 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.

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12 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

13 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).

14 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

15 Poore, J. and T. Nemecek. 2018. Reducing food's environmental impacts through producers and consumers. Science 360 (6392): 987-992. DOI: 10.1126/science.aaq02

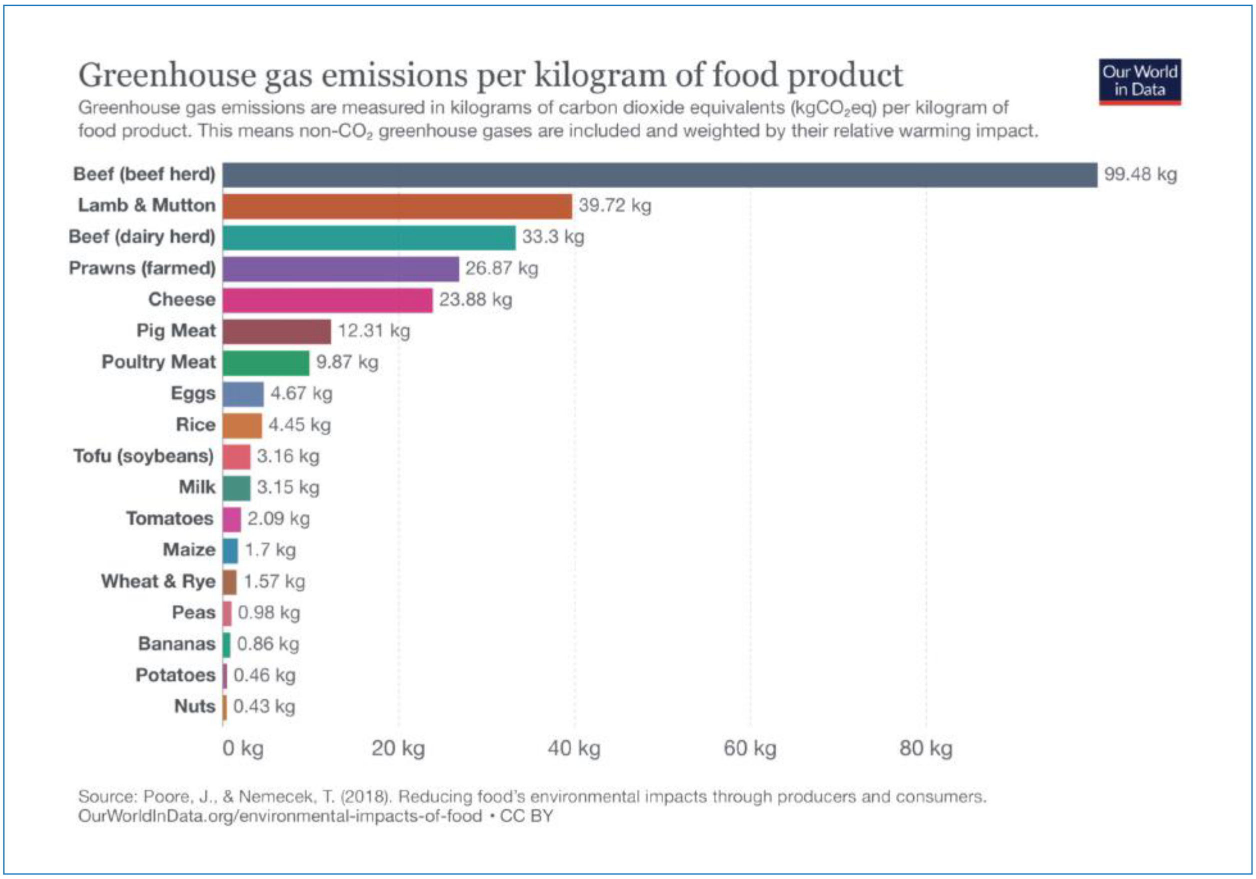

Fig. 1.2. Greenhouse gas emissions per kg of various food products (Poore and Nemecek, 2018[15]; Richie and Roser, 2020)[16]

Ritchie and Roser (2020)[16] have worked with data available from the meta-analysis by Poore and Nemecek (2018)[15] 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[17]. 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[18]. 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[19].

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[16] 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

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

[18] 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/.

[19] Notarnicola, B., Tassielli, 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.

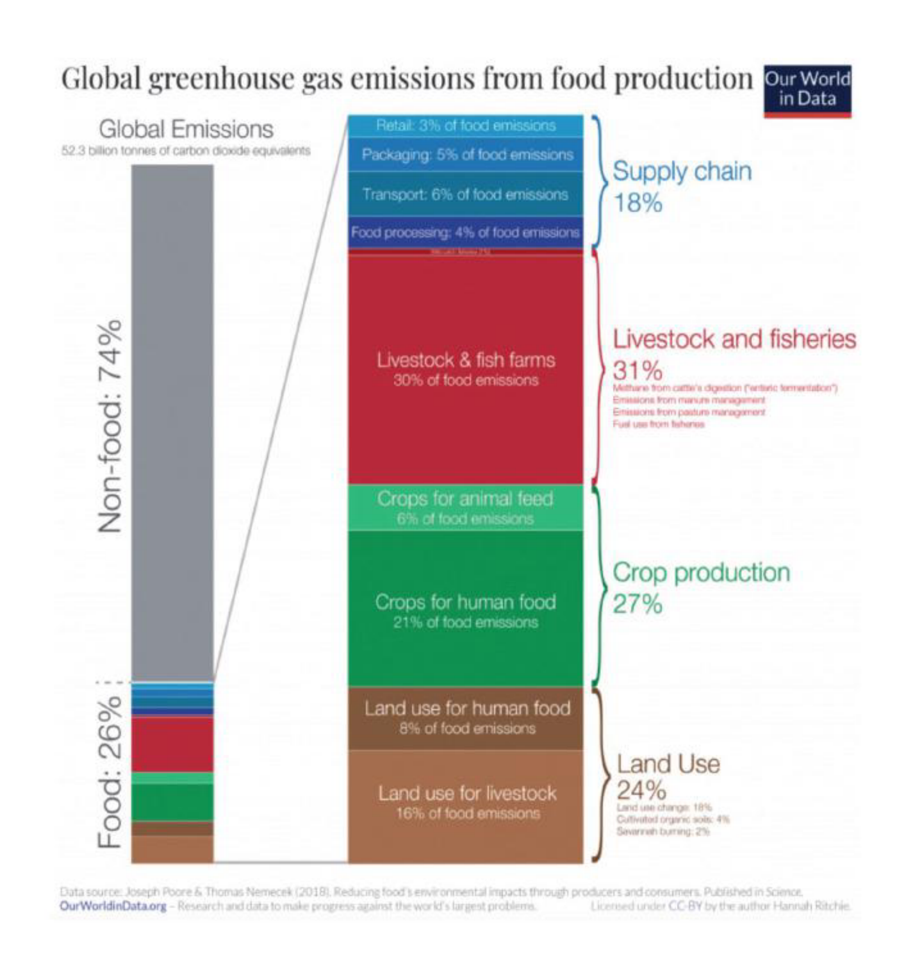

Fig. 1.3. GHG emissions from the food system, total and by areas.
https://ourworldindata.org/environmental-impacts-of-food, Author: Hannah Ritchie

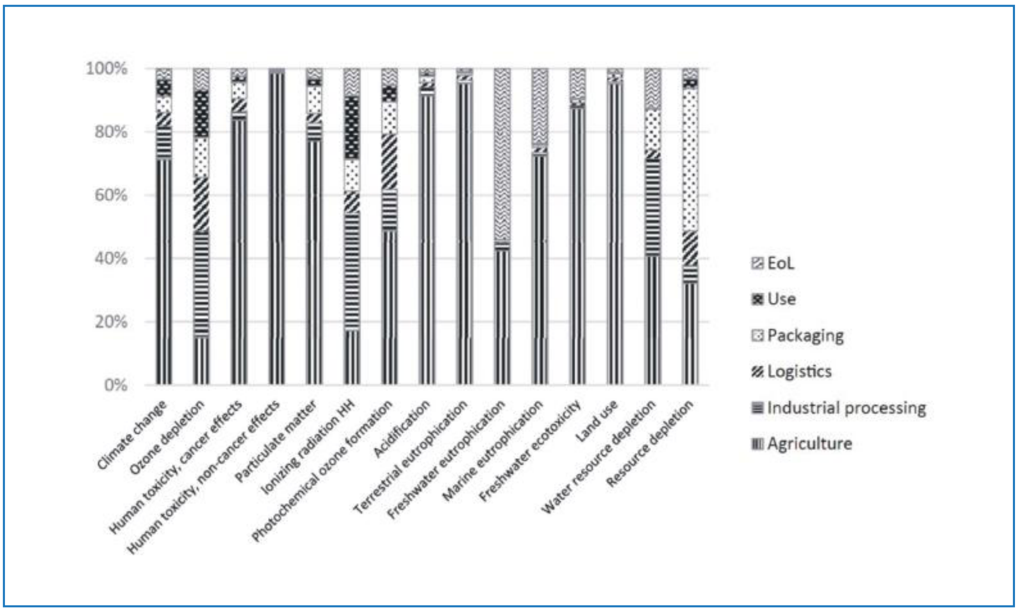

Fig. 1.4. Relative contribution of the 6 life-cycle phases to the impact of the entire basket in each impact category for the EU. (Notarnicola, et.al., 2017)[19]. [EoL = End of Life]

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. CCC Order License ID 5471400467922
https://www.sciencedirect.com/science/article/pii/S0959652616307570
Direct URL: 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[20] 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"[21, 22]. 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"[23]. 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 21st century than what it seemed to be in the preceding one. In the 20th 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[24] 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[25]. 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[26, 27]. 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[28]. 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.

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20 Malassis L., 1994. Nourrir les hommes. Paris, Flammarion (coll. "Dominos" 16).

21 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..

22 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

23 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

24 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

25 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.

26 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-Uribe, 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.

27 Jimenez, D., Perez-Uribe, 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

28 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[29] (HLPE, 2020), in terms of patterns and volumes as well as energy consumption and related practices. Caron et. al. (2018)[7] 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[30, 31], and including the reduction of food loss and waste[31, 32];
- The contribution to the viability and sustainability of ecosystems, including soil health and better fertilisation practices; and
- A renaissance of rural territories.

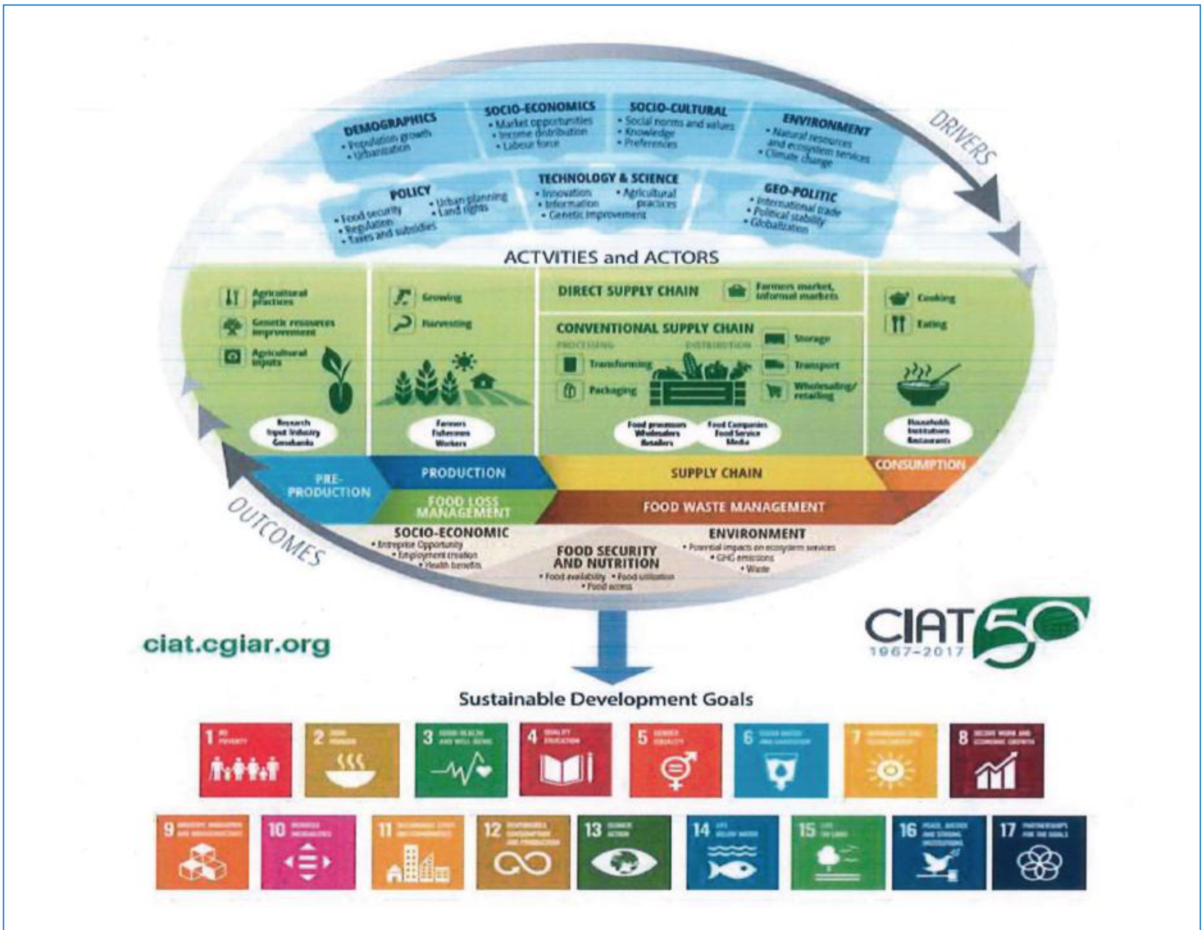

Fig. 1.5. An Interpretation of the Food and Agriculture System illustrating Drivers, Activities, Actors and Outcomes. All elements of growing, harvesting, storing, processing, distributing, consuming and managing the food and agriculture system are encompassed by UN's Sustainable Development Goals (SDGs).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

Author: Norman R. Scott (member of the group of authors for this chapter), and R. Paul Singh https://www.nae.edu/276571/Guest-Editorss-Note-Science-and-Engineering-to-Transform-the-Food-and-Agriculture-System-for-the-Future

[29] 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

[30] 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.

[31] 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.)]..

[32] 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.)].

[33] 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[34]. However, emissions can vary substantially by product within the food supply chain.

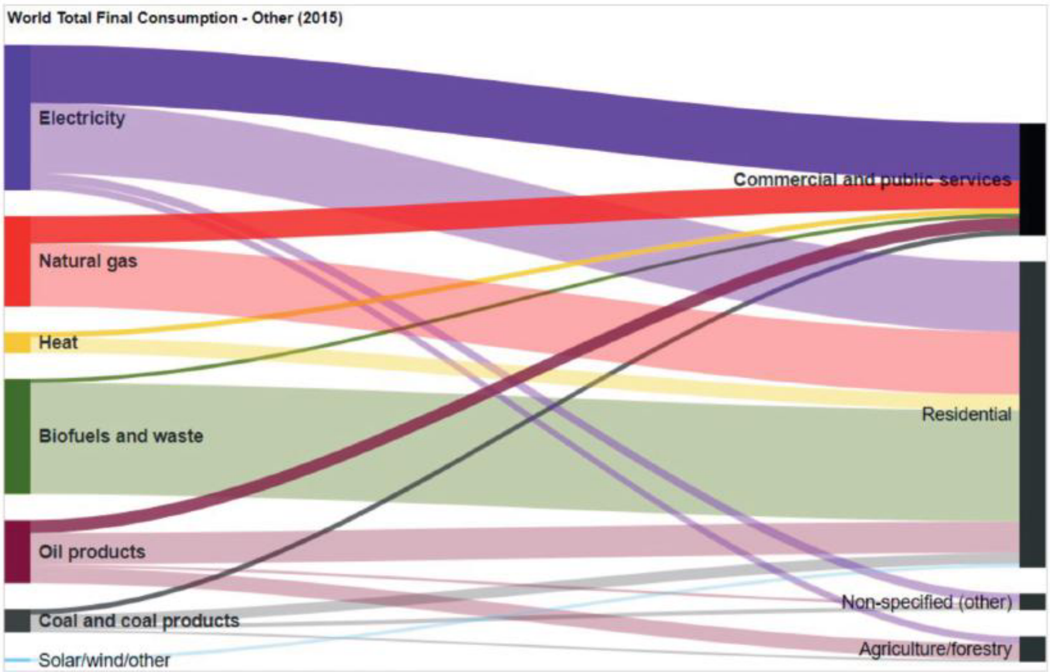

Fig. 1.6. World total energy consumption by the different sectors (IEA, 2018). Reproduced with permission

[34] 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/.

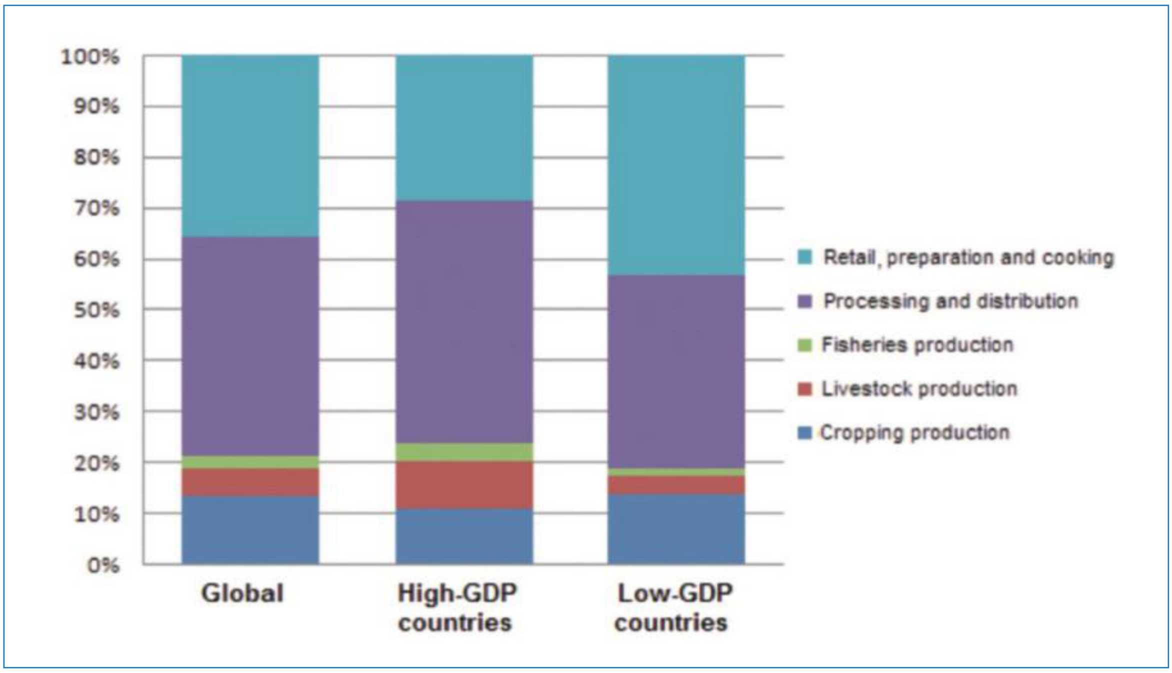

Fig. 1.7. Distribution of shares of end-use total energy across the food supply chain for global consumption (2.64 x 10^{12} kWh) and high-GDP (1.39 x 10^{12} kWh) and low-GDP (1.25 x 1012 kWh) FAO (2011)[35] Energy smart food for people and climate, Issue Paper. Food and Agriculture Organization of the United Nations. Reproduced with Permission.
https://www.fao.org/3/i2454e/i2454e.pdf

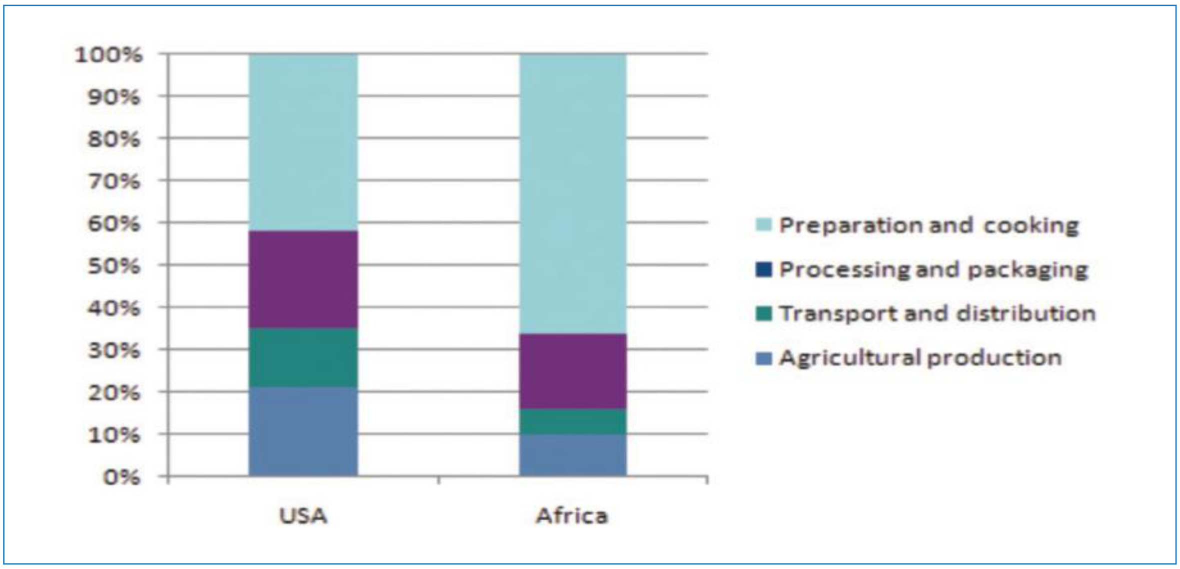

Fig. 1.8. High-GDP and low-GDP differences in energy inputs in the food supply chain. FAO (2011)[35] Energy smart food for people and climate, Issue Paper. Food and Agriculture Organization of the United Nations. Reproduced with Permission.
https://www.fao.org/3/i2454e/i2454e.pdf

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[36].

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

[36] 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).

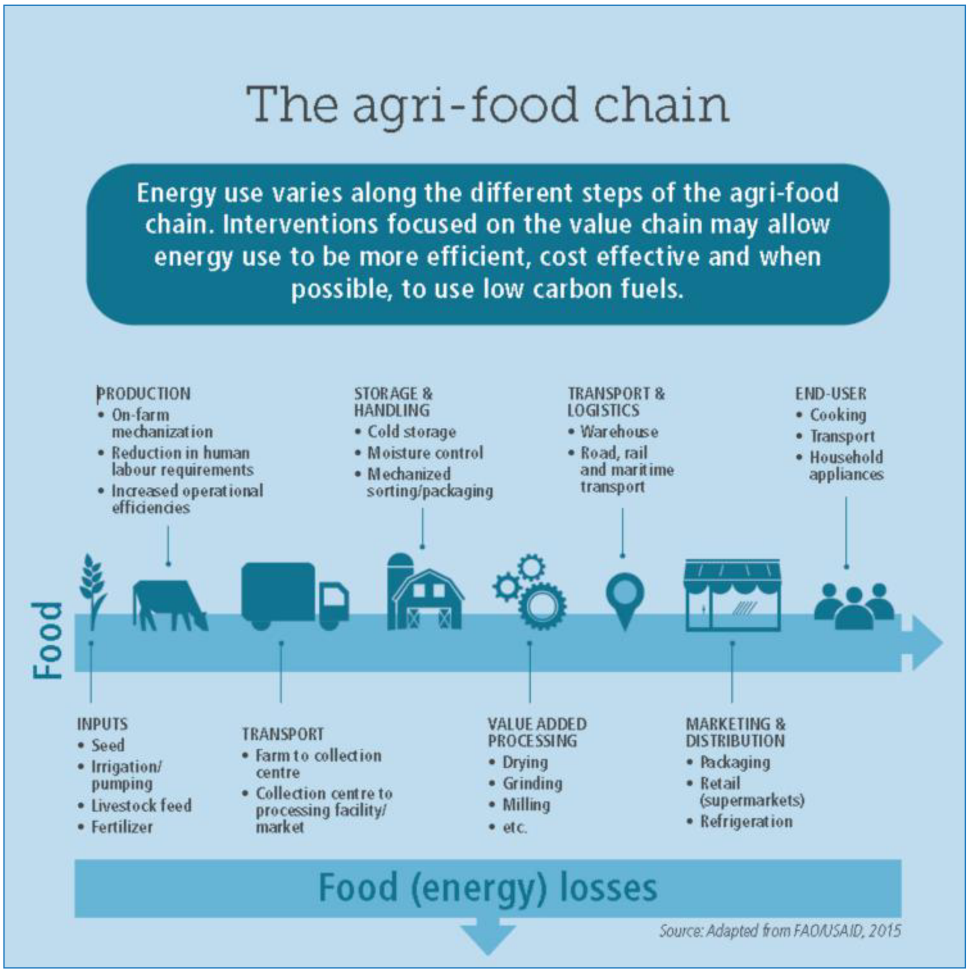

Fig. 1.9. Energy ports along the food-agriculture sector supply chain
Source: Tweet Food and Agriculture Organisation
"Adapted from FAO/USAID, 2015"
https://twitter.com/fao/status/987069593238851585

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%[37]. 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[38]. About 60% of this energy is consumed directly via the use of gaso-line, 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.

37 FAO. 2022 Agrifood chains I Energy. www.fao.org/energy/agrifood-chains/en/

38 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[39, 40].

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.

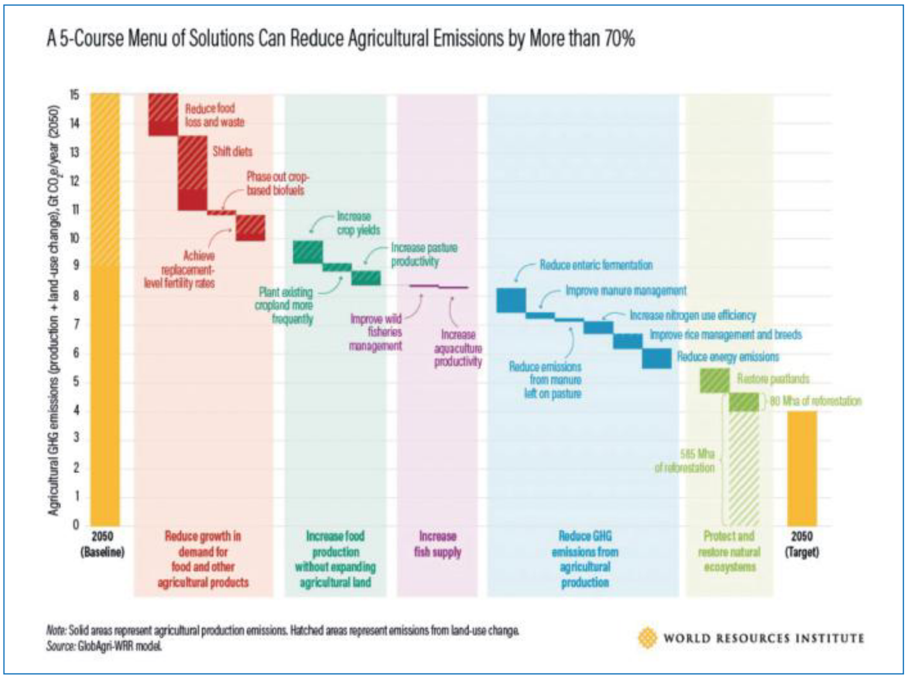

Fig. 1.10. Items suggested to reduce emissions within the production component of the FAS illustrating existing best practices, behaviour change and possible policy options [41]

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

[40] Hefft, D. I., & Higgins, Ŝeamus. 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

[41] 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 33, Page 427, Reproduced with Permission. https://www.wri.org/research/creating-sustainable-food-future

The IPCC (2022)[42] 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) $GtCO_{2e}$/yr of which 2.5 (1.5-3.9) $GtCO_{2e}$/yr is viewed as plausible based on a range of GWP_{100} value for CH_4 and N_2O. When accounting for diverted agricultural production only, the feasible potential is 1.7 (1 – 2.7) $GtCO_{2e}$/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[43]. *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[44]. 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[45].

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 alone has a greater carbon, GHG, land-use, water, nitrogen, or energy footprint than a similar mass of postharvest loss excluding consumer waste. This is due to the inclusion of transport, packaging, processing, distribution, and preparation at home, all of which is finally “embedded” in consumer waste. Similarly, on average, energy “waste” from consumer waste alone is equivalent to eight times that resulting from postharvest loss where consumer waste is not included[46].

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[47].

[42] IPCC -AR6- WGIII. 2022. Chapter 7. Agriculture, Forestry and Other Land Uses

[43] 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

[44] 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.

[45] HLPE, 2014. ibid

[46] 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 (https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/resource%20revolution/mgi_resource_revolution_full_report.pdf).

[47] HLPE, 2014. Ibid

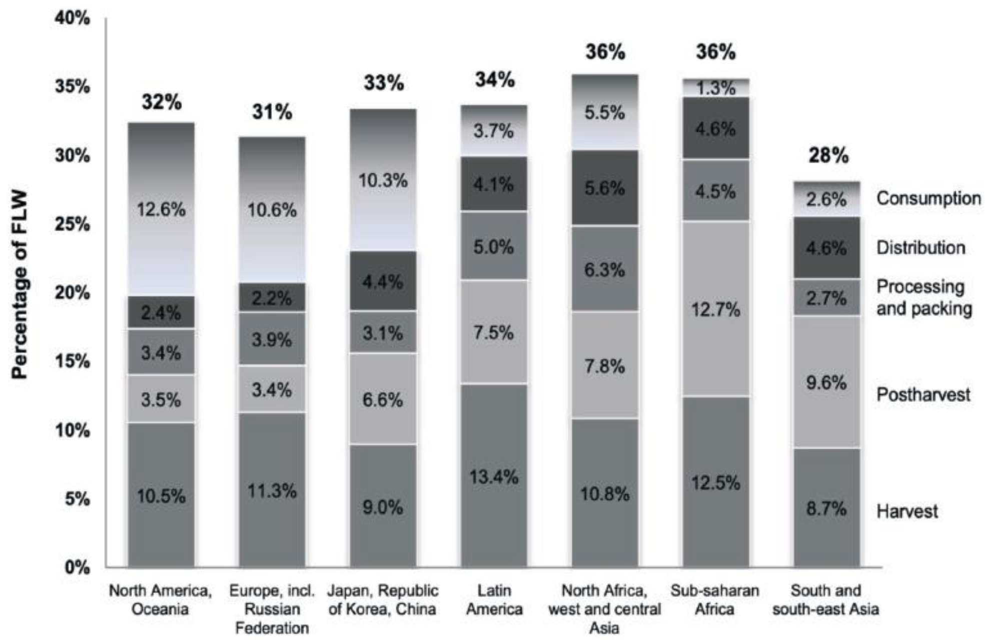

Fig. 1.11. Distribution of FLW along the food chain in the different regions of the world (HLPE, 2014)[45] HLPE Report 8, 2014: Food losses and waste in the context of sustainable food systems. A report by The High Level Panel of Experts on Food Security and Nutrition, June 2014, Page 27, Reproduced with permission. https://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/HLPE_Reports/HLPE-Report-8_EN.pdf

The IPCC (2022) estimates, with medium confidence, that reduced FLW has a large global technical mitigation potential of 2.1 (0.1-5.8) $GtCO_{2e}$/yr including savings in the full value chain using GWP_{100} and a range of IPCC values for CH_4 and N_2O. They suggest potential plausible values as 3.7 (2.2-5.1) $GtCO_{2e}$/yr.

3.3. Valuing new food resources through technology

Global meat consumption is estimated to increase 3% per year to 2040[48, 49]. However, several groups[49, 50] 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[51, 52]. 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[53] 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;

48 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;

49 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-2fbe-079dab3e5647?t=1608631513000 .

50 Tubb, C., and Seba, T. 2019.Rethinking food factory: The next generation indoorand 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.

51 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;.

52 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.

53 Purdy, C. 2020. Billion Dollar Burger. Penguin Random House. 252 p.

(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; (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[54, 55, 56].

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[57]. 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[58]. 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[59]. 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)[60] 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.

54 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.

55 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

56 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

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

58 Heller, M., Keoleian, G. 2018.Beyond Meat's beyond burger life cycle assessment: A detalled 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..

59 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.

60 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.

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[61]. 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[62].

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[63].

A Life Cycle Assessment (LCA)[64] and a (TEA) techno-economic assessment[65] 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[66, 67, 68, 69] 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[69]. 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

61 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.

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

63 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.

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

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

66 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;

67 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;

68 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.

69 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[70]. The concept of the greenhouse, as we have come to know it today, began in the Netherlands and then England in the 17th 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_2 in nutrient solution, electrical conductivity for dissolved salts in nutrient solution, CO_2 of inside air, and light intensity from the sun and supplemental lighting, and PAR (photosynthetic active radiation) in mol/m^2/d. Quality and optimum plant growth is dependent on plants getting an optimum daily quantity of PAR (mol/m^2/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_2 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[71].

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[72, 73, 74, 75]. 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[76].

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

70 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.

71 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.

72 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

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

74 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.

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

76 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[77].

Fig. 1.12. An example of a vertical farm
Source: Photo by Markus Spiske on Unsplash, free to be reproduced.
https://unsplash.com/fr/photos/9cHVqn9bBpQ

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[78].

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"[79]; 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)[80]".

[77] 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/AEF.24.76

[78] IPCC -AR6- WGIII. 2022. Chapter 7. Agriculture, Forestry and Other Land Uses.

[79] NRDC (National Resources Defense Council). 2022. Regenerative Agriculture: Farm Policy for 21st Century. regenerative-agriculture-farm-policy-21st-century-report-pdf.

[80] 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.

Agroecological approaches acknowledge 6 major shifts[81] (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[82]. 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[83].

There is general agreement that regenerative agriculture and agroecology practices improve soil health and provide environmental benefits. Some researchers report[84] 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.

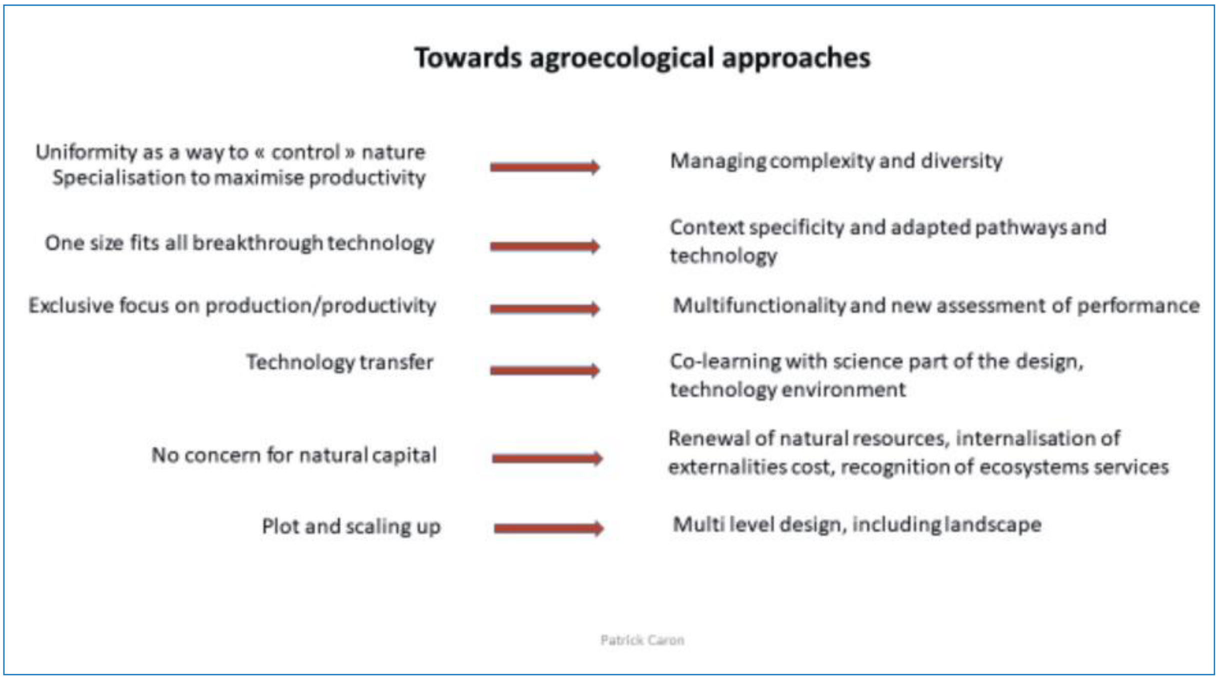

Fig. 1.13. Towards agroecological approaches[85]

81 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.

82 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.

83 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.

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

85 Caron P. (member of the group of authors for this chapter), 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, 2021.

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[86], "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[87]. 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) $GtCO_2$/yr and in grasslands 1.0 (0.2-2.6) $GtCO_2$.

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_3), 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[88]. 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)[89]. 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,

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86 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.

87 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.

88 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.

89 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) $GtCO_{2e}$/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_2 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[90]. 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)[91]. 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 km² 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_2) 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^{15}g) C/year but these numbers are highly uncertain[91] 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.

90 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.

91 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

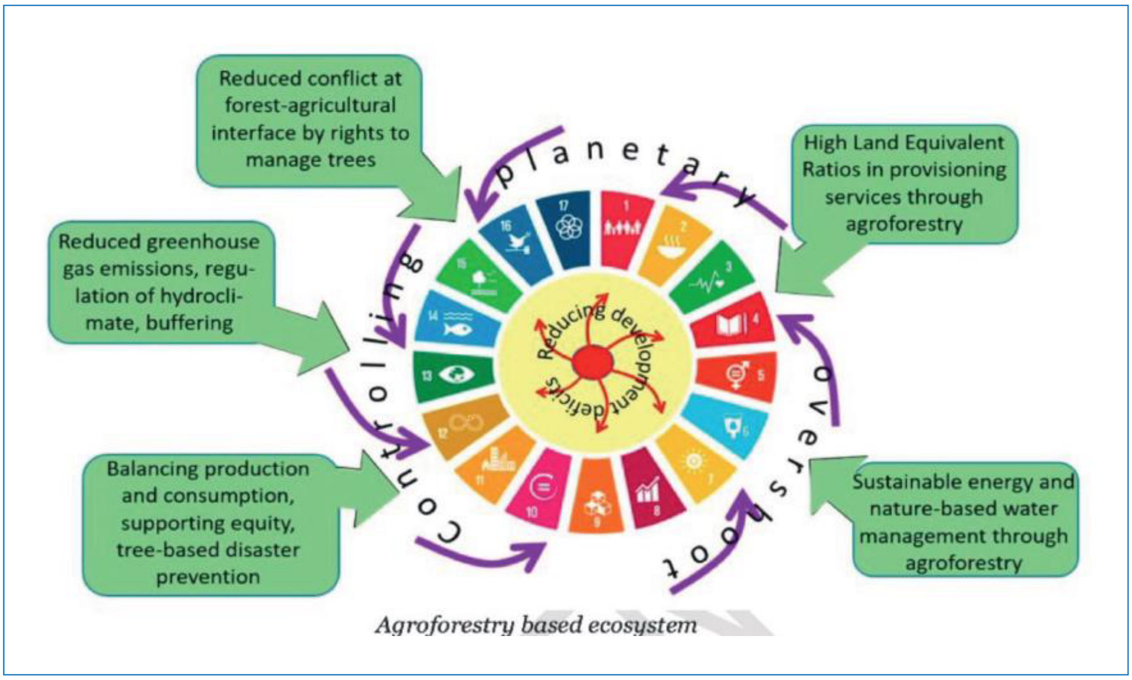

Fig. 1.14. Illustration of agroforestry systems for ecosystem services and economic benefits[92]
Source: Van Noordwijk, M. 2021. Agroforestry-Based Ecosystem Services: Reconciling Values of Humans and Nature in Sustainable Development. Land 2021, 10(7),699
https://www.mdpi.com/2073-445X/10/7/699

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)[93] 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[94], cold plasma[95], pulsed electric field[96], ultrasound[97], and microwaves[98]. 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.

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92 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

93 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

94 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

95 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

96 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

97 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

98 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[99] 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[100].

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[101, 102, 103]. 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[104].

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99 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.

100 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.

101 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..

102 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

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

104 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

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[105]. 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[106].

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-& fatt 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[107]. 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.

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[105] OECD-FAO. 2017. Meat-Agricultural Outlook 2018-2027. Chapter 6. www.fao.org/3/i9166e/i9166e_chapter6_meat.pdf.

[106] 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

[107] 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
Source: Norman R. Scott (member of the group of authors for this chapter), Intec Open, Evolution of The Soil-Based Agriculture and Food System to Biologically-Based Indoor Systems, Page 15.
https://www.intechopen.com/chapters/78111

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[108]. 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[109]. 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.

[108] 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..

[109] 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^3/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*[110] 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 1st, 2nd, and 3rd 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
1st generation	Edible crops (sunflower, sugarcane, corn, soybeans, palm, rapeseed, etc.)
2nd generation	Agro-residues (lignocellulosic)
3rd generation	Algae
4th generation	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[111]: bio-renewables constitute about 47% while the balance is ascribed to wind, geothermal, hydro, and solar facilities.

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

111 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[112].

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)[113]. 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[114] 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[115] while the estimate for Nigeria is 96%[116]. 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_2 sequestration and the release of CO_2 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[117].

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

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

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

114 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.

115 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.

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

117 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[118]. 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[119].

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^3 and 40 million m^3 plants respectively for heating water, cooking, and lighting. The World Bioenergy Association estimated an annual global biogas production of 30-40 billion m^3 (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_2.

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[120]. 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_1 to C_4 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 in 2020 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 1st, 2nd and 3rd generation technologies (see definitions in *Table 1.2.*). The food vs. energy crop debate has however encouraged the development of 2nd 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.

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118 Chemical Engineering Progress. 2021. Special section: Renewable natural gas. September 2021 issue. www.aiche.org/cep

119 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/

120 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.

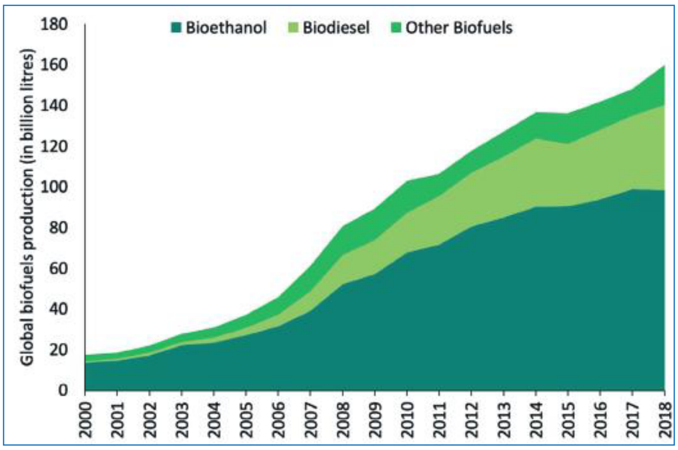

Fig. 1.16. Global production history for liquid biofuels (Chemical Engineering Progress, 2021)[118]
Source: Global Bioenergy Statistics 2020 produced by World Bioenergy Association, Chapter 6, p49, Figure 58. Reproduced with permission
Reference: https://www.iea.org/data-and-statistics
(https://www.worldbioenergy.org/uploads/201210%20WBA%20GBS%202020.pdf)

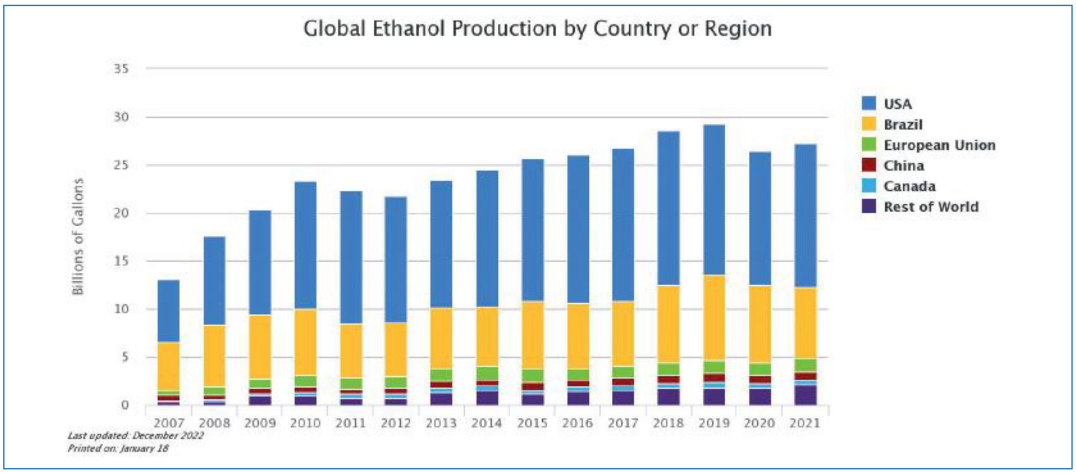

Fig. 1.17. Trends in bioethanol production for selected countries/regions
Source: "Global Ethanol Production by Country or Region" 2023. U.S. Department of Energy, Alternative Fuels Data Center. Accessed January 15, 2023.
afdc.energy.gov/data/10331
https://afdc.energy.gov/data/10331

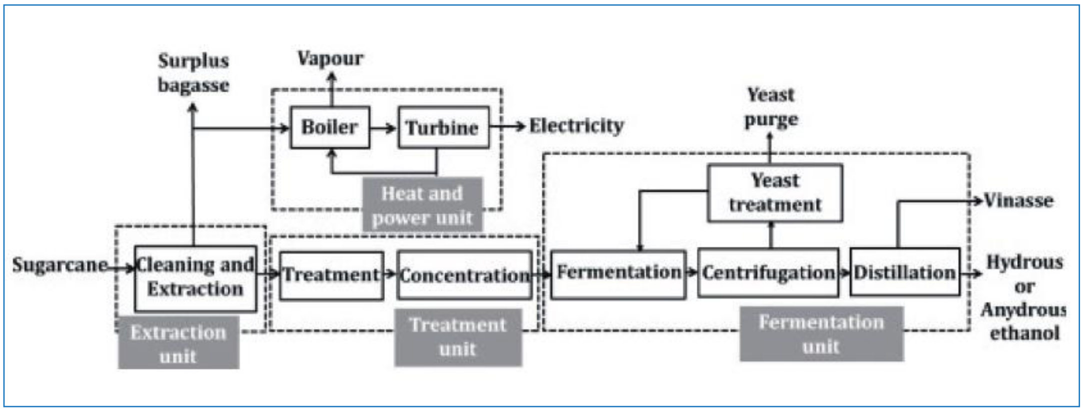

Fig. 1.18. Block diagram of a Brazilian ethanol production facility
Source: Assessing the Performance of Industrial Ethanol Fermentation Unit Using Neural Networks. CCC RightsLink License N° 5471400721280
https://www.sciencedirect.com/science/article/pii/B9780444642356500322

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[121, 122]. An improvement in the production of biodiesel beyond the 1st 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 2nd and 3rd generation biodiesel production route[123] as schematically depicted in *Fig. 1.19.*.

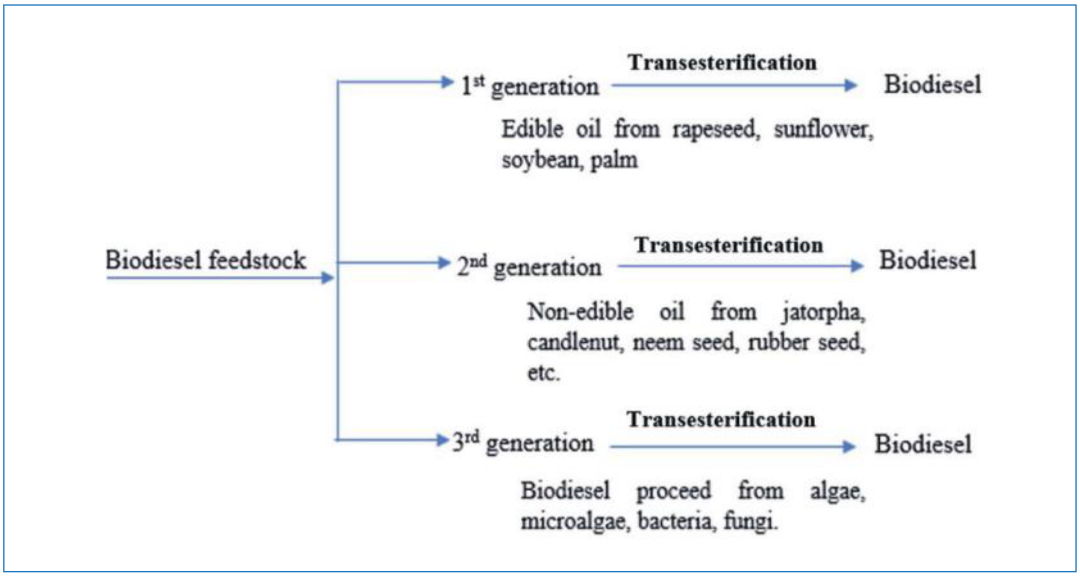

Fig. 1.19. Biodiesel production technology pathways
Source: Shaah et.al., 2021, A review on non-edible oil as a potential feedstock for biodiesel: physicochemical properties and production technologies, Page 4, Royal Society of Chemistry CC BY-NC
https://pubs.rsc.org/en/content/articlehtml/2021/ra/d1ra04311k

121 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;

122 Karapatsia, A., Penloglou 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.

123 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[124]. 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)[125] 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[126]. 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[127]. 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[128] 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[129]. Medium evidence suggests that biochar has a technical potential of 2.6 (0.2-6.60) $GtCO_{2e}$/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[130] 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.

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124 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.

125 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.

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

127 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

128 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. Envior. Sci. Technol. 44: 827-833. 10.1021/es902266r

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

130 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

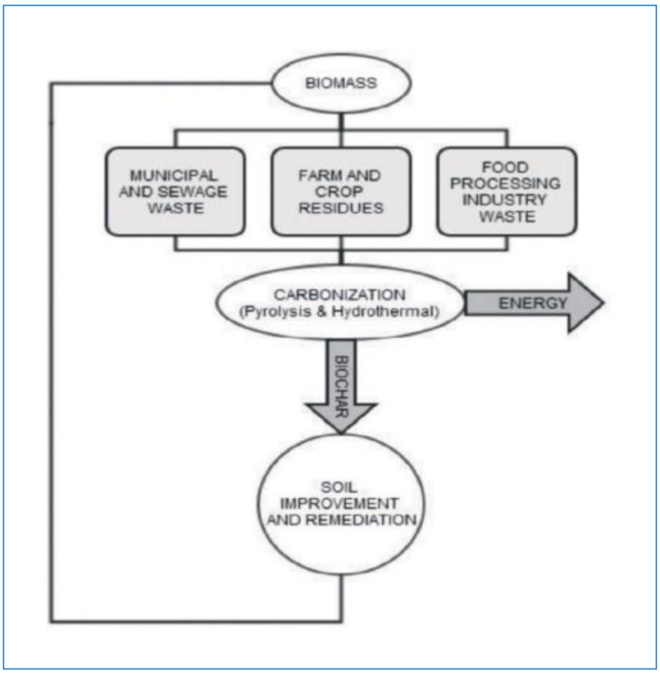

Fig. 1.20. Biochar production from the valorisation of organic waste.

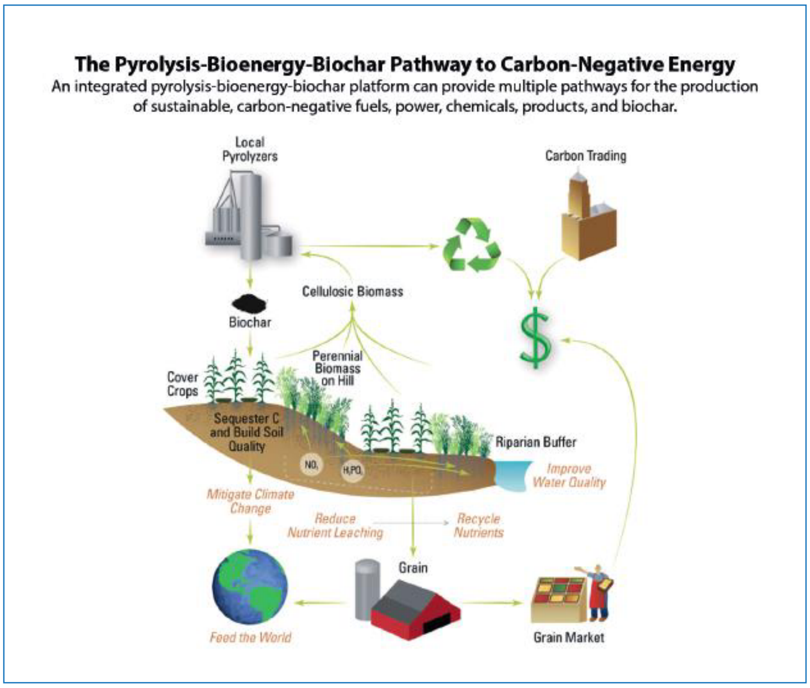

Fig. 1.21. Synergy between agriculture, energy and environment via the biochar loop (Farm Energy, 2019)[131]
Source: David Laird, Iowa State University, reproduced with permission
https://www.biorenew.iastate.edu/research/thermochemical/biochar/pathway.

[131] https://www.academia.edu/25743192/Woody_Feedstocks_Management_and_Regional_Differences_In_Braun_R_D_Karlen_and_D_Johnson_ed_Sustainable_Feedstocks_for_Advanced_Biofuels_Sustainable_Alternative_Fuel_Feedstock_Opportunities_Challenges_and_Roadmaps_for_Six_U_S_Regions

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)[132] has been further developed and analyzed by Adeh et al. (2019)[133], Baron-Gifford et al. (2019)[134], Dinesh et al. (2018)[135], Dupraz et al. (2011)[136]. 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[135]. 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[133]. 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[137].

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[138]. 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. Reproduced with permission
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

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

[133] 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

[134] 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)

[135] 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

[136] 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.

[137] 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

[138] 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[139], 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, member of the group of authors for this chapter.

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.

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

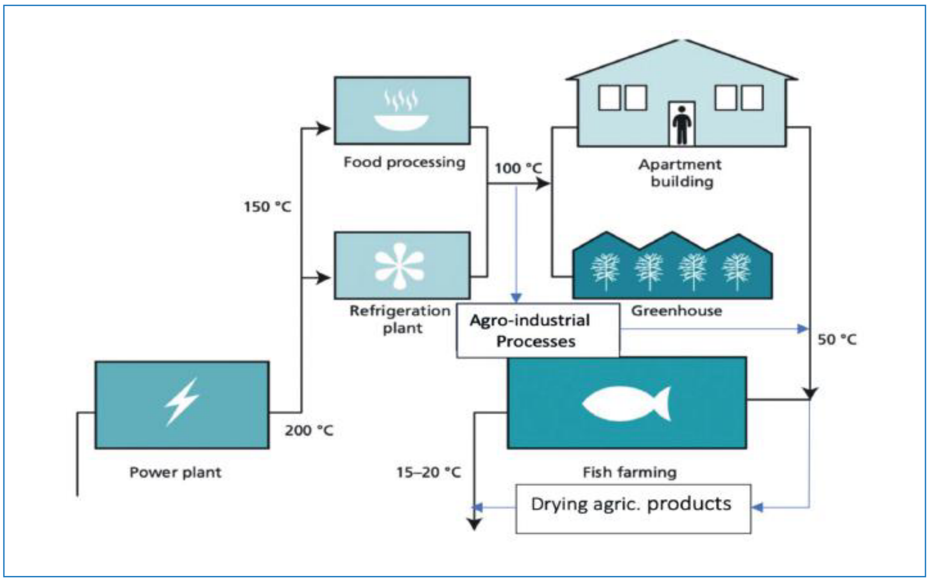

Fig. 1.24. Cascade use of geothermal energy illustrating applications in the FAS (adapted and modified from Lund, 2010,[140] Fig. 11) https://doi.org/10.3390/en3081443

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[141]. 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.

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[140] Lund, J.W. 2010. Direct utilization of geothermal energy. Energies 3(: 1443-1471. https://doi.org/10.3390/en3081443

[141] Future Farming. 2022. A website with continuing information frequent updates in racking electric autonomous equipment, including tractors. https.www.futurefarming.com

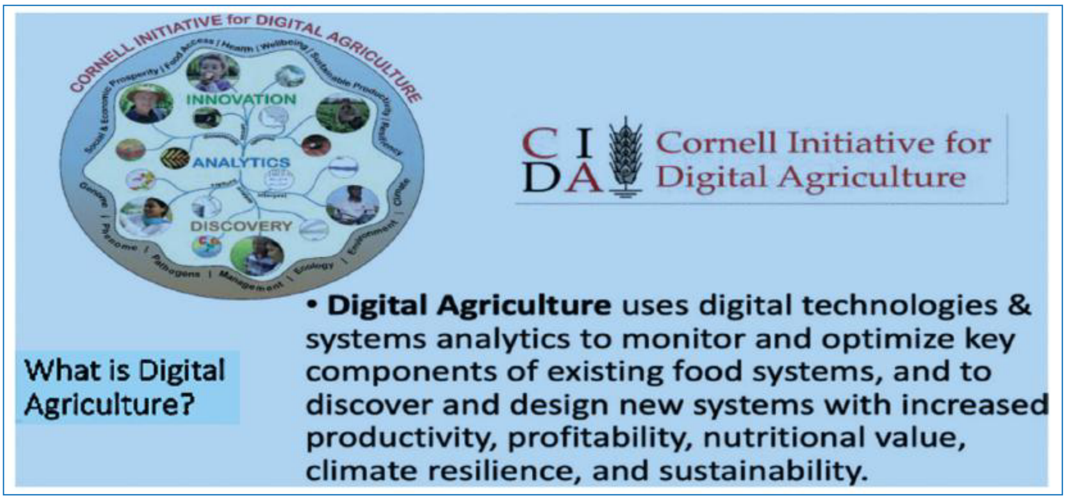

Fig. 1.25. Use of digital technologies in agriculture
Source: Intec Open, Evolution of The Soil-Based Agriculture and Food System to Biologically-Based Indoor Systems, Norman R. Scott, member of the group of authors for this chapter, Page 5

The capability of Digital Ag ultimately depends on the integration and connectivity of critical elements for a successful system, broadly categorised by Scott (2020)[142] 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)[143] 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, em-

[142] 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

[143] 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

ploy microwave technology to kill weeds, and other methods); (ii) to spot the onset of plant diseases or pests 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)[144] 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)[145], 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.

[144] Future Farming. 2022. A website with contininingi information frequent updates in racking electric autonomous equipment, including tractors. https.www.futurefarming.com

[145] 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[146] and on the environment[147]. 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[146]. 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 environemental impact by 19%. However, no-till management on croplands has become a controversial approach for storing carbon in soil due to conflicting findings[148].

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[149]. 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[150]. 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[151].

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”.

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146 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

147 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

148 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

149 ISAAA. (International Service for the Acquisition of Agri-Biotech Applications). 2020. ISAAA Brief 55-2019: Global status of biotech crops. 2020. www.isaaa.org

150 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

151 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[152, 153]. 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-barcodes 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[154, 155, 156, 157, 158] 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.,

[152] 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

[153] 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

[154] 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; Gillbertson et.al., 2020; Kah et al., 2019.

[155] 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

[156] 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

[157] 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

[158] 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 20th 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[159] 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.

[159] 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 arragements 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

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

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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_2 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_2 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][1].

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_2 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.

[1] 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

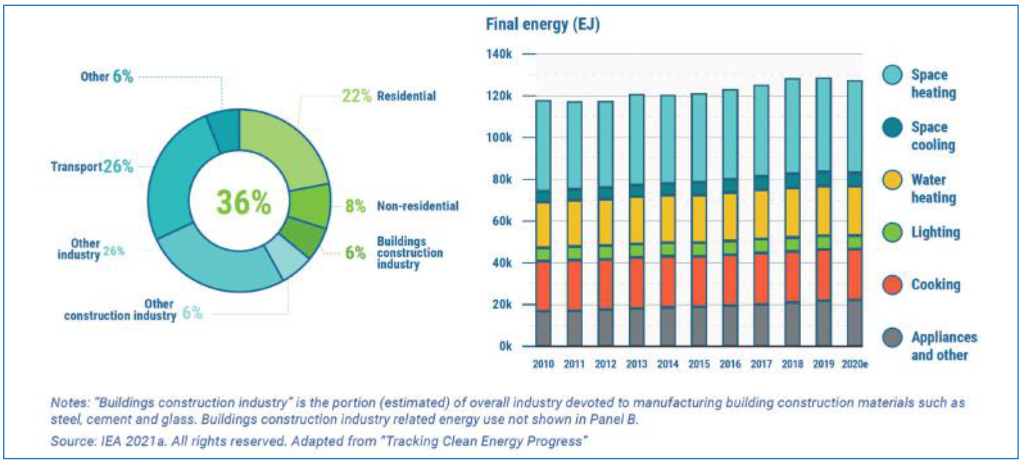

Fig. 2.1. Final energy consumption for construction and by use
Source: United Nations Environment Programme (2021). "2021 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Cector", Nairobi, Page 39, Copyright © United Nations Environment Programme, 2021, Reproduced with permission. 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. *See:* https://www.igsd.org/chinas-green-and-high-efficiency-cooling-action-plan-a-model-for-cooling-efficiency-ambition/

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_2 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 kWhe/m²/yr as a world average, as opposed to the 30–50 kWhe/m²/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^2 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^2. 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.

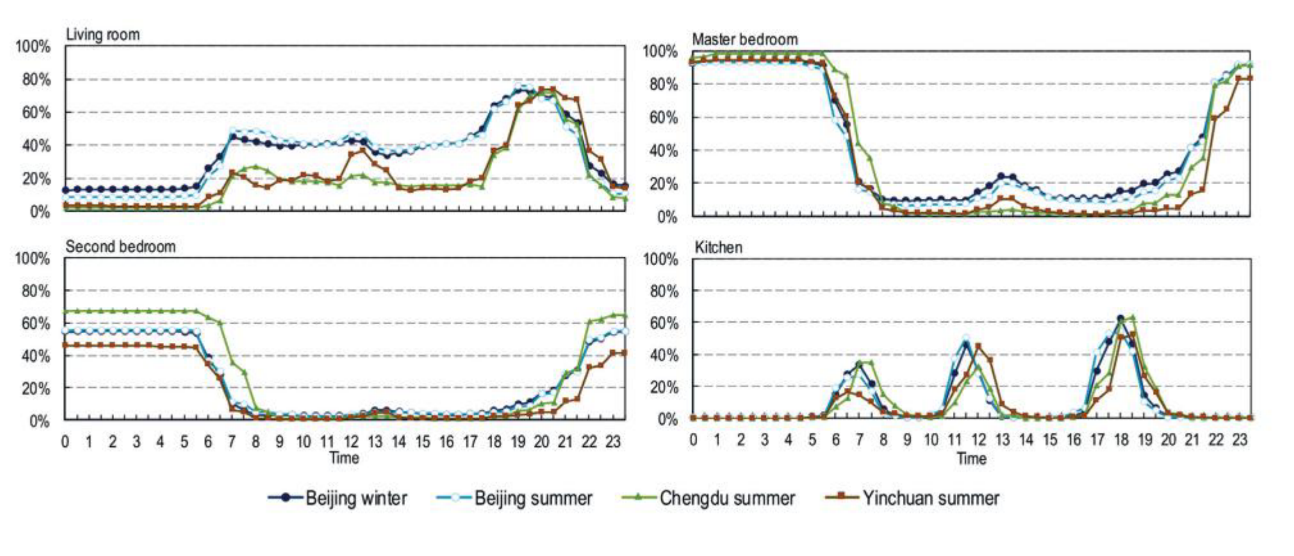

Fig. 2.2.a. Occupancy rate of urban households in China (data source: questionnaire survey on 3 400 households in 4 Chinese cities) (Hu et al. 2019). Provided by Tsinghua University with Permission for Reproduction.

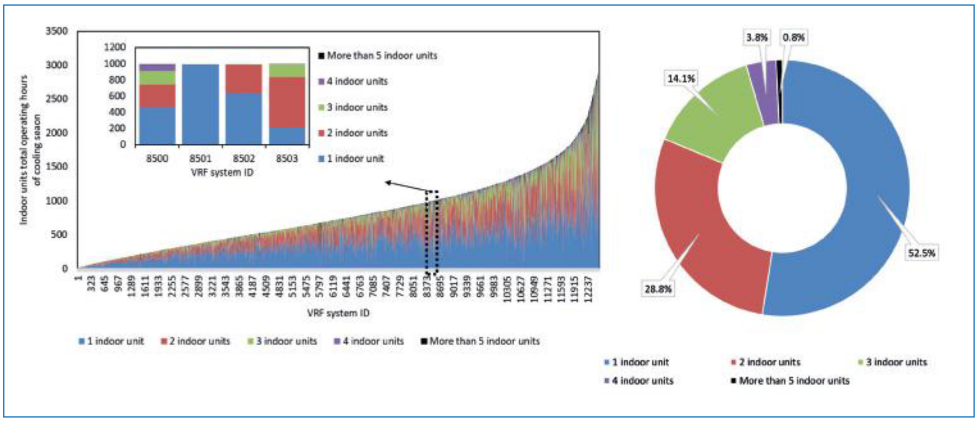

Fig. 2.2.b. VRF operation patterns of urban households in China
(data source: 12 527 VRF systems operation monitoring data in residential buildings in in 2020). Provided by Tsinghua University with Permission for Reproduction.

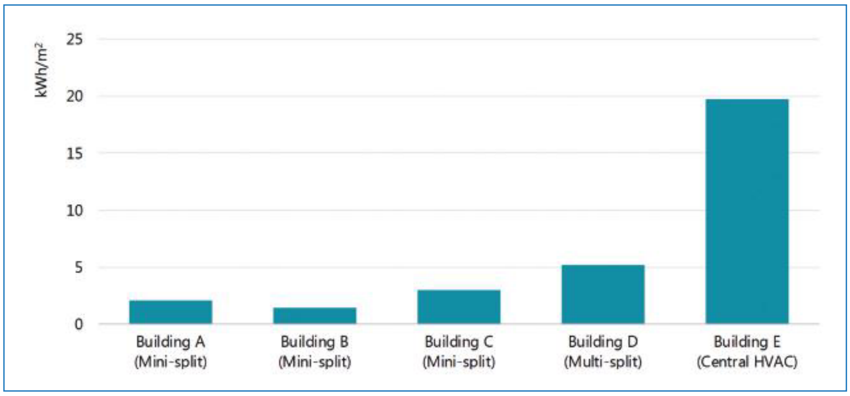

Fig. 2.2.c. Average cooling energy intensities by different system in urban residential building
(data source: monitoring of 5 buildings in Beijing in 2006)(IEA, 2019). Reproduced with permission

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^2, 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_2 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 equipment 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. (https://beeindia.gov.in/content/escos-0)

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 (https://www.giz.de/en/worldwide/111395.html)). 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.

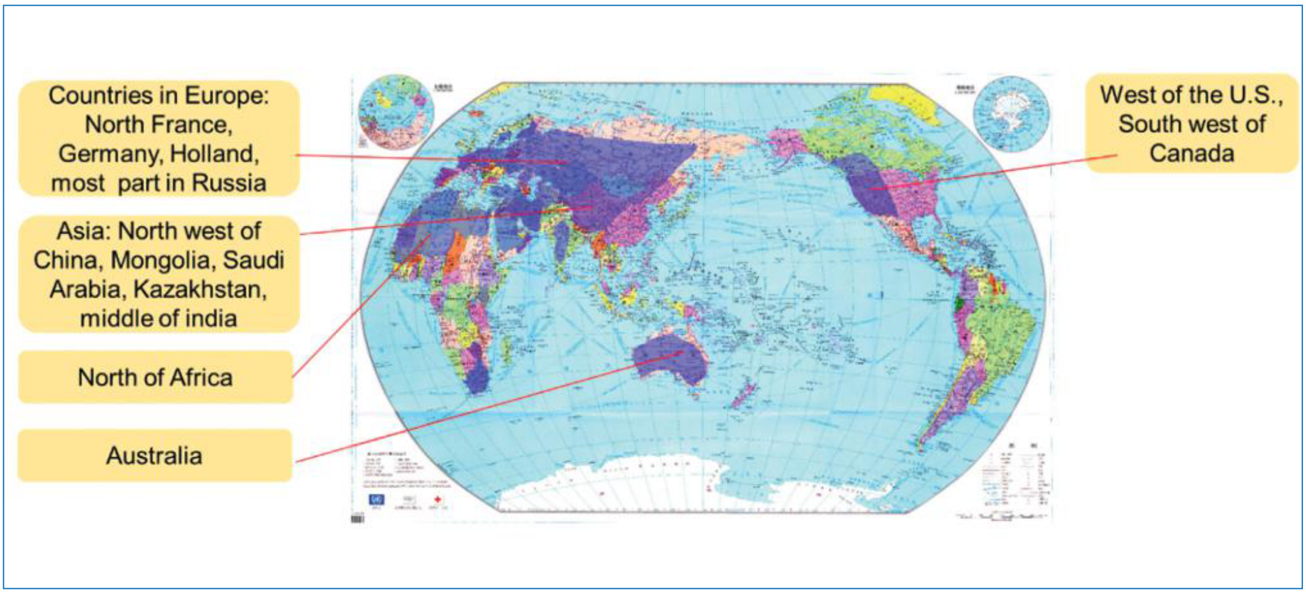

Fig. 2.3. Regions of the world where IEC or DEC technologies may be suitable

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.
>
> *See also:* 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. *See also:* https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1805795#:~:text=The%20India%20Cooling%20Action%20Plan,going%20programmes%2F%20schemes%20of%20the

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 gives an overview of recent announcements and updates from around the world of cooling. *See also:* https://www.cleancoolingcollaborative.org/blog/cooling-at-cop26-what-did-and-didnt-happen/

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.

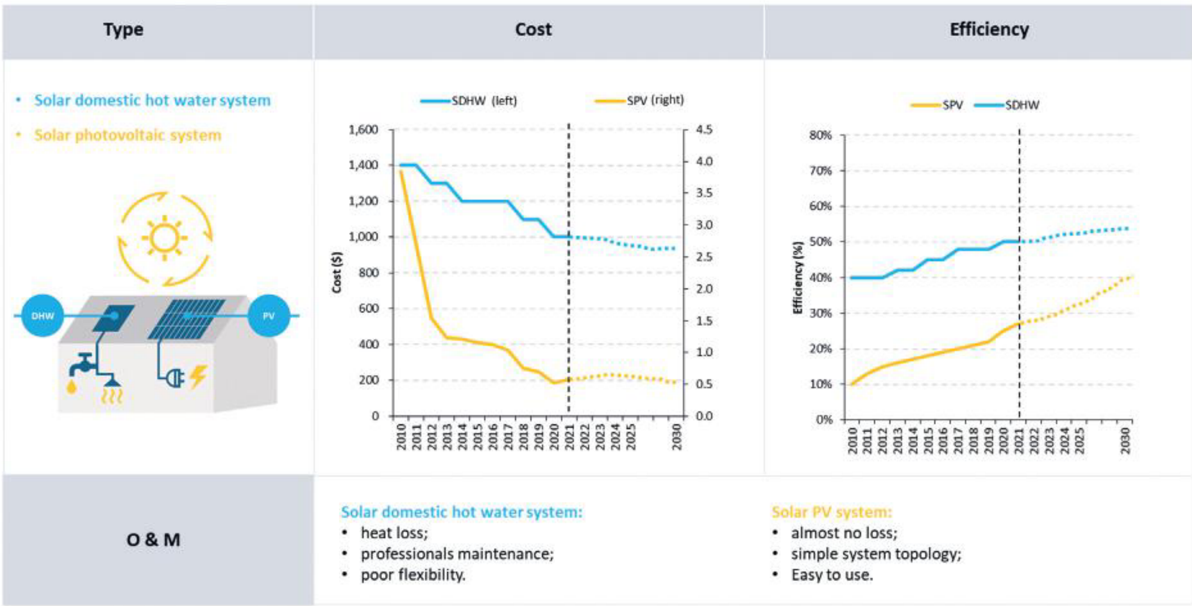

Fig. 2.4. Comparison of solar domestic hot water system and photovoltaic system. Provided by Tsinghua University with Permission for Reproduction.

The heat pump water heater with CO_2 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_2. Rotary, swing and scroll are the three main types of compressors applicable to the current CO_2 water heat pump. To reduce the high throttling loss resulting from the high-pressure difference of CO_2, 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. *See also:* https://www.sans10400.co.za/energy-usage/

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 (NOx), 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[2].

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[3].

Concerning CO_2 emissions, considering that, to obtain 1 kWh by gas combustion, about 200 g of CO_2 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_2 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[4].

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2 Methane and NOx 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).

3 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.

4 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. (see also https://www.seforall.org/events/global-launch-of-the-nigeria-integrated-energy-planning-tool and https://nigeria-iep.sdg7energyplanning.org/)

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[5].

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^2 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^2 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 IEA, An Energy Sector Roadmap to Carbon Neutrality in China[EB/OL], https://iea.blob.core.windows.net/assets/9448bd6e-670e-4cfd-953c-32e822a80f77/Anenergysector-roadmaptocarbonneutralityinChina.pdf

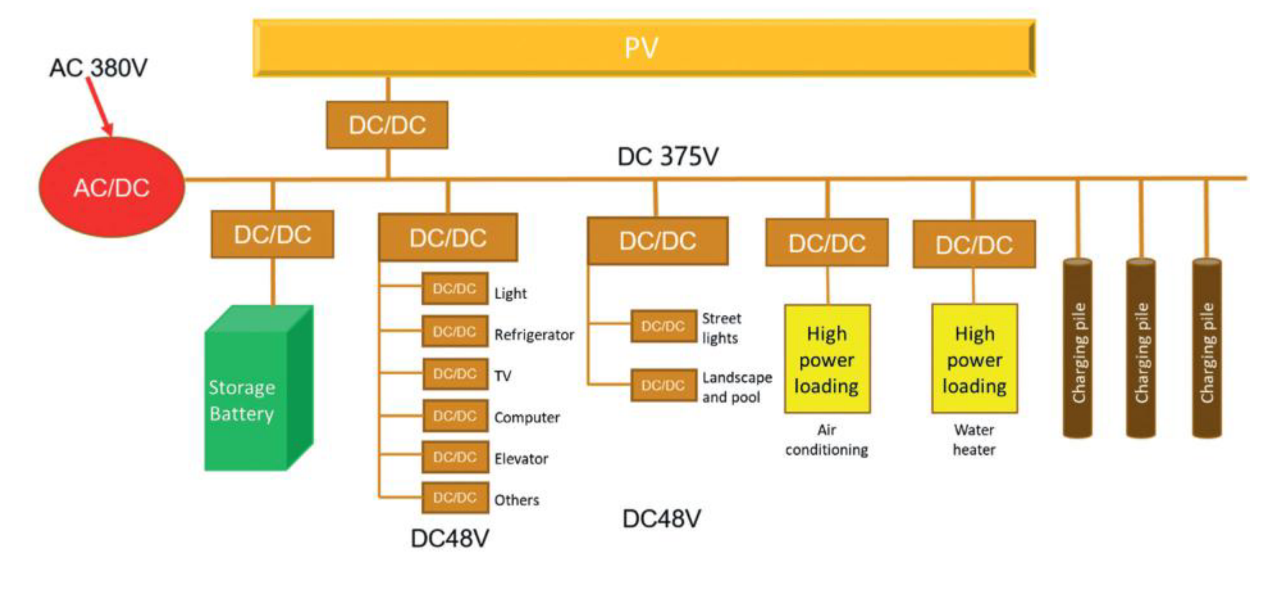

Fig. 2.5. Example of PEDF buildings power system in China. Provided by Tsinghua University with Permission for Reproduction

5 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 (*see also:* https://www.activehouse.info/cases/ibr-future-complex/). The IBR Future Complex in Shenzen is a 6259 m^2 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 allows increased efficiency and limited losses.

Depending on the energy sources, the CO_2 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_2 emissions, even though burning does induce CO_2 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 (CH4) and CO_2. 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_2 and CH4 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 CH4 and CO_2, 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_2 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).

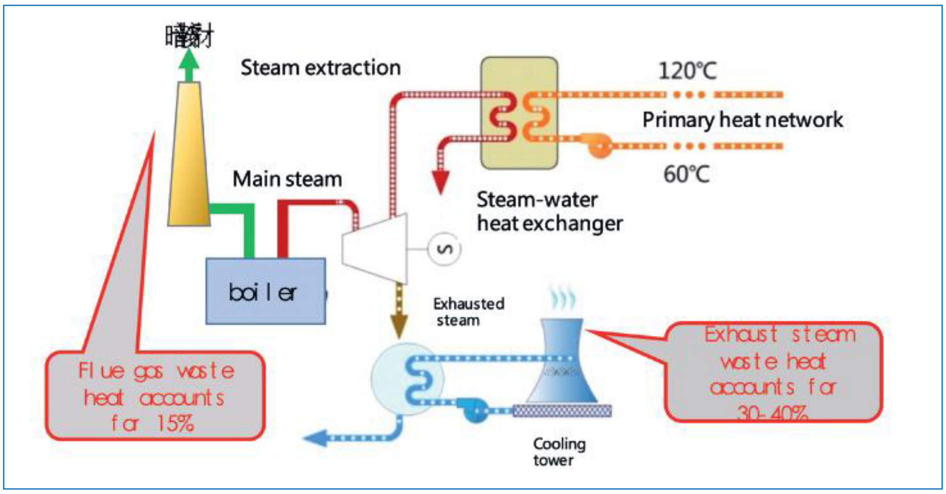

Fig 2.6. Potential waste heat recovery in thermal power plants (from Building energy research center of Tsinghua University, 2019 Annual report on China building energy efficiency, Beijing, China Architecture& Building Press, 2019 (in Chinese).) Provided by Tsinghua University with Permission for Reproduction

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 m² 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.

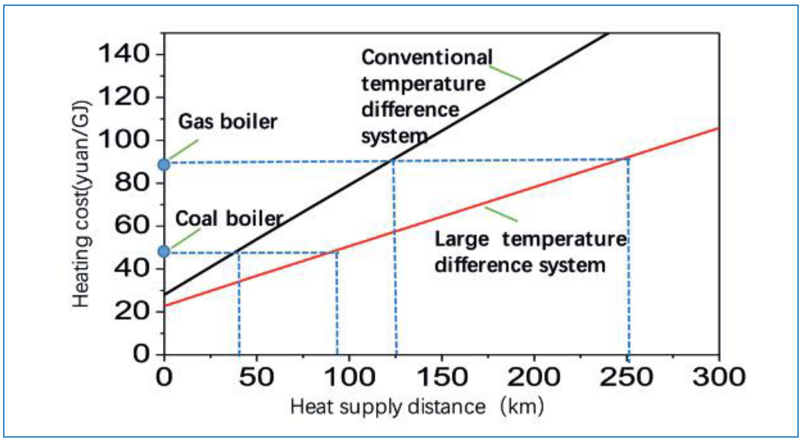

Fig 2.7. Costs of conventional heating systems and large temperature difference heating systems for large heat supply distances. Provided by Tsinghua University with Permission for Reproduction

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_2 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[6]. 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

[6] 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 (1st), Zurich (2nd), Oslo (3rd), Taipei City (4th), Lausanne (5th), Helsinki (6th), Copenhagen (7th), Geneva (8th), Auckland (9th) and Bilbao (10th).

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.

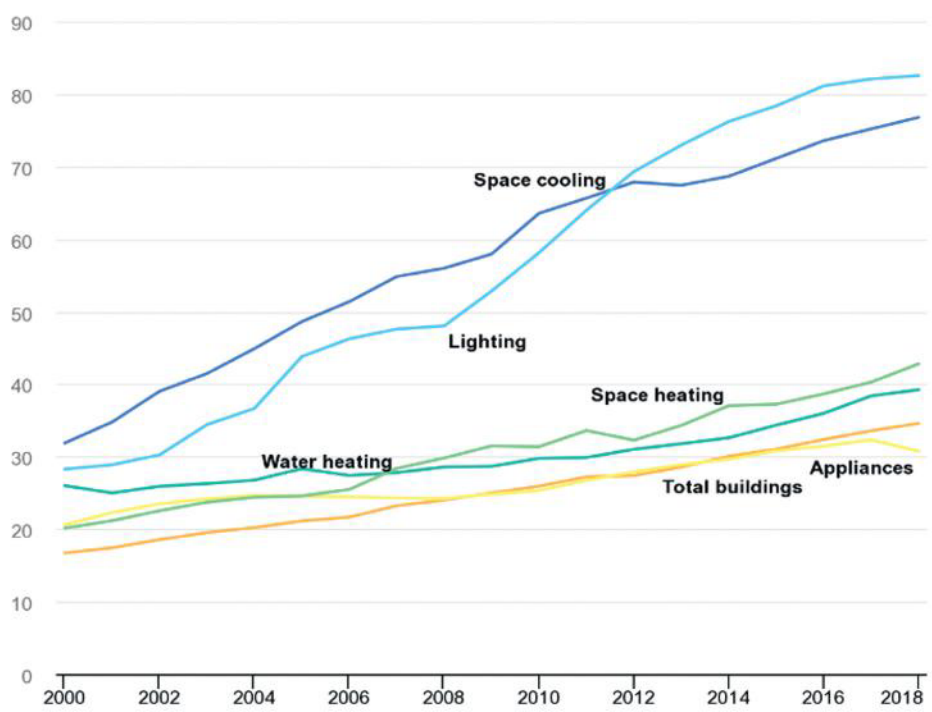

Fig. 2.8. Percentage of the world population benefiting from a standard or a label by energy useChina building policies, a case study
Source: Policy coverage of total final energy consumption in buildings, 2000-2018 - Last updated 26 Oct 2022. Reproduced with permission.
https://www.iea.org/data-and-statistics/charts/policy-coverage-of-total-final-energy-consumption-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. *See also:*

1) Ministry of Housing and Urban-Rural Development of PRC, The 13th Five-Year Plan of building energy efficiency and Green Building development[EB/OL], https://www.mohurd.gov.cn/gongkai/fdzdgknr/tzgg/201703/20170314_230978.html, 2017-03-14.

2) The State Council of China, Action Plan to Peak Carbon by 2030[EB/OL], http://www.gov.cn/zhengce/content/2021-10/26/content_5644984.htm, 2021-10-26.

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. *See:* https://www.ecsa.co.za/news/News%20Articles/181113_DPW_Green_Building_Policy.pd

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 000m² and private sector buildings greater than 2 000m² 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 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. *See:* https://mediatum.ub.tum.de/doc/1649455/document.pdf

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). *See:* https://www.researchgate.net/publication/266382605_A_NEED_FOR_CURRICULUM_ENHANCEMENT_IN_ARCHITECTURAL_EDUCATION_TO_PROMOTE_SUSTAINABLE_BUILT_ENVIRONMENT_AND_MITIGATE_CLIMATE_CHANGE

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[7] 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_2 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.

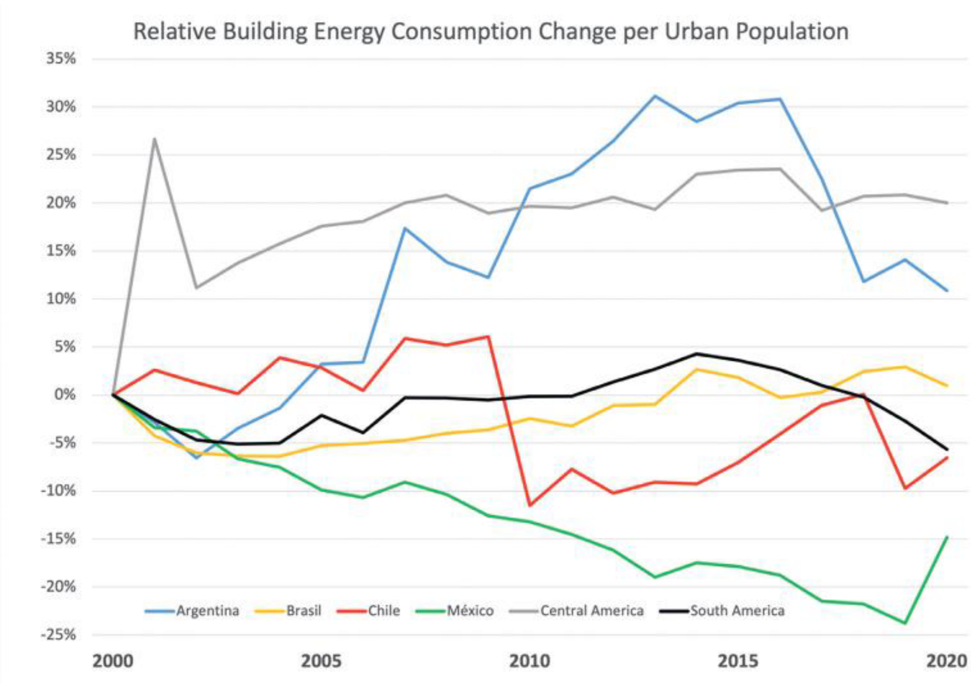

Fig. 2.10. Relative Building Energy Consumption from Utilities (BECU) change since 2000 per-capita in urban areas.
Source of data: PANORAMA ENERGÉTICO DE AMÉRICA LATINA Y EL CARIBE, 2021, OLADE, Organización Latinoamericana de Energía
https://sielac.olade.org/WebForms/Reportes/VisorDocumentos.aspx?or=453&documentoId=10000014
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.

[7] 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[8].

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

[8] 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.

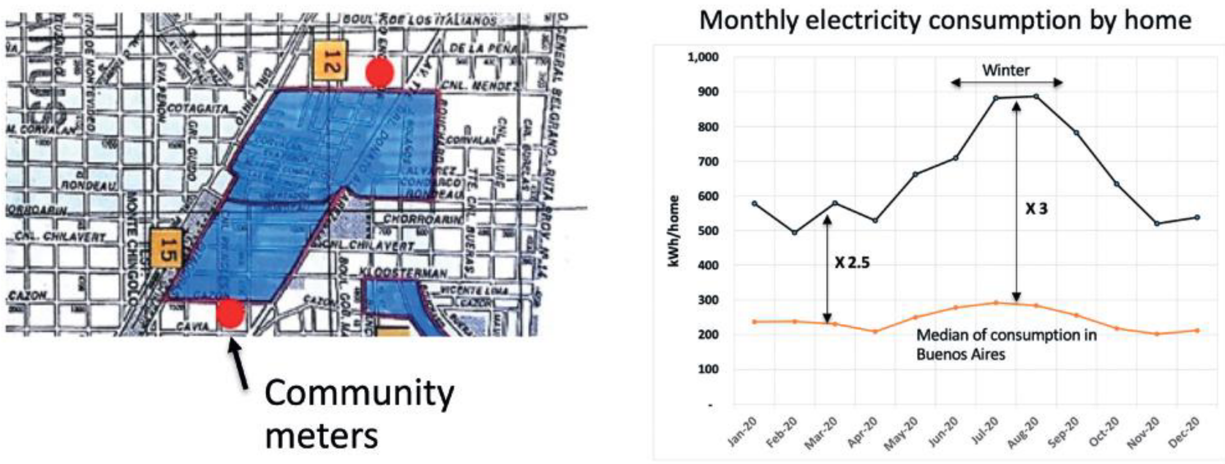

Fig. 2.12. Community meters in slums (left) and monthly electricity consumption by home in Buenos Aires vs. slums (right)

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_2/MWh, this means USD 52 million/yr of subsides and 250 000 tonnes CO_2/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_2/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_2/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 tonCO2/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_2/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 Consumption = 160 lt/day	Service life: 15 years
Energy savings	168 kWh/month	
Cost of equipment	1500 USD	
NPV of Subsidies	1467 USD	
NVP/Cost	98 %	
CO2 emission avoided	0.821 tonCO2/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_2/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 Subsides	4,503 USD	
NPV/Cosgt	90 %	
CO2 emission avoided	2.196 tonCO2/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_2/yr of GHG.

	District Heating
Description	Space and water heating from heat generated in Combined Cycle Power Plant
Hyphotesis	Natural Gas Power Plant 589 MW (Puerto Nuevo) . Distance = 1000 m
Energy savings/home	3,428 kWh/year
NPV of Subsides/home	3,396 USD
NPV x 8,000 homes	27 MMUSD
Cost of Distrit heating	To be computed
CO2 emission avoided	11,160 tonCO2/yr

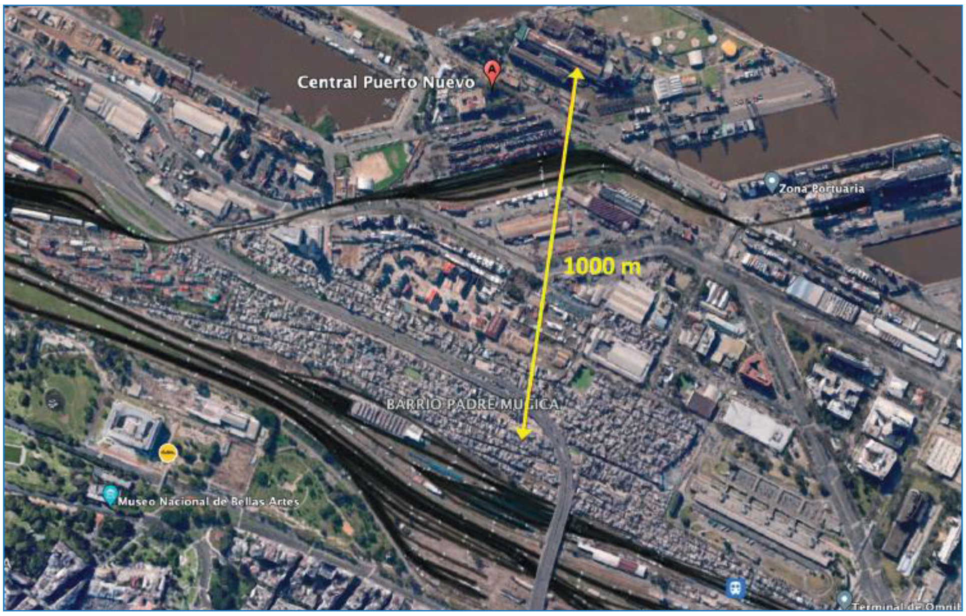

Fig. 2.13. Distance between the existing thermal power plant and the 'Villa 31' (Buenos Aires, Argentina)
Source: Google Earth

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_2/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_2/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_2/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	Subsides Avoided	Net Present Value of Subsides Avoided	CO_2 avoided
	MMUSD	MMUSD/yr	MMUSD	tonCO_2/yr
Efficient Refrigerator	7.1	0.46	3.9	2 191
Solar Thermal for hot water	12.0	1.4	11.7	6 564
Solar Photovoltaic	40.0	3.7	36.0	17 570
District heating	To be computed	2.3	27.2	11 160
Present Situation		Present Susides MMUSD/yr		Present CO_2 toncCO_2/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 m2 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. Constructed from an aerial photograph from Google Earth

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^2 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_2 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.

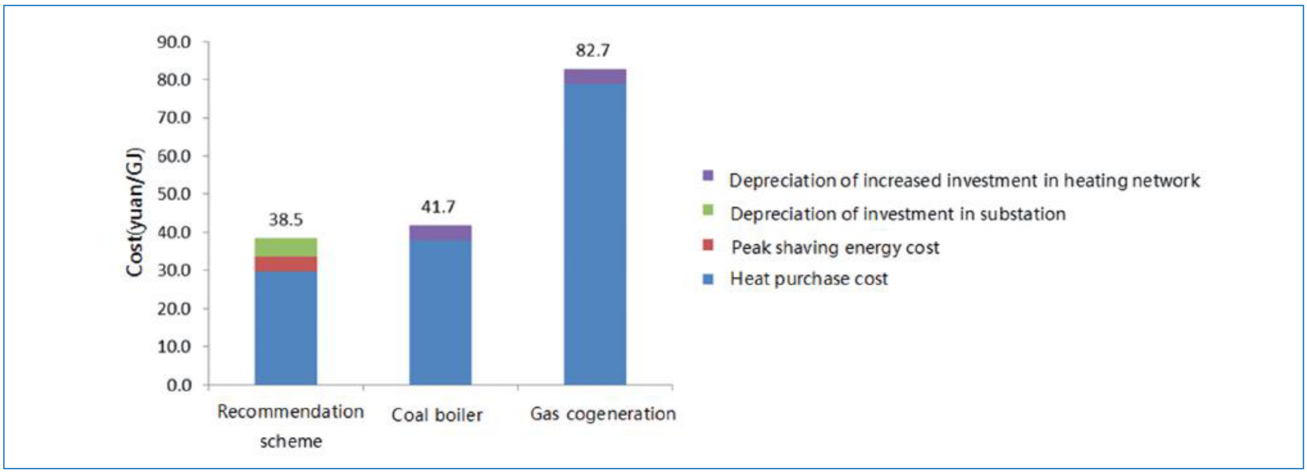

Fig. 2.15. Total heating cost comparison. Provided by Tsinghua University with Permission for Reproduction

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 m² 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_2 emission, SO2 emission, and NOx emission are some 106 000 tonnes, 340 tonnes, and 300 tonnes per year respectively.

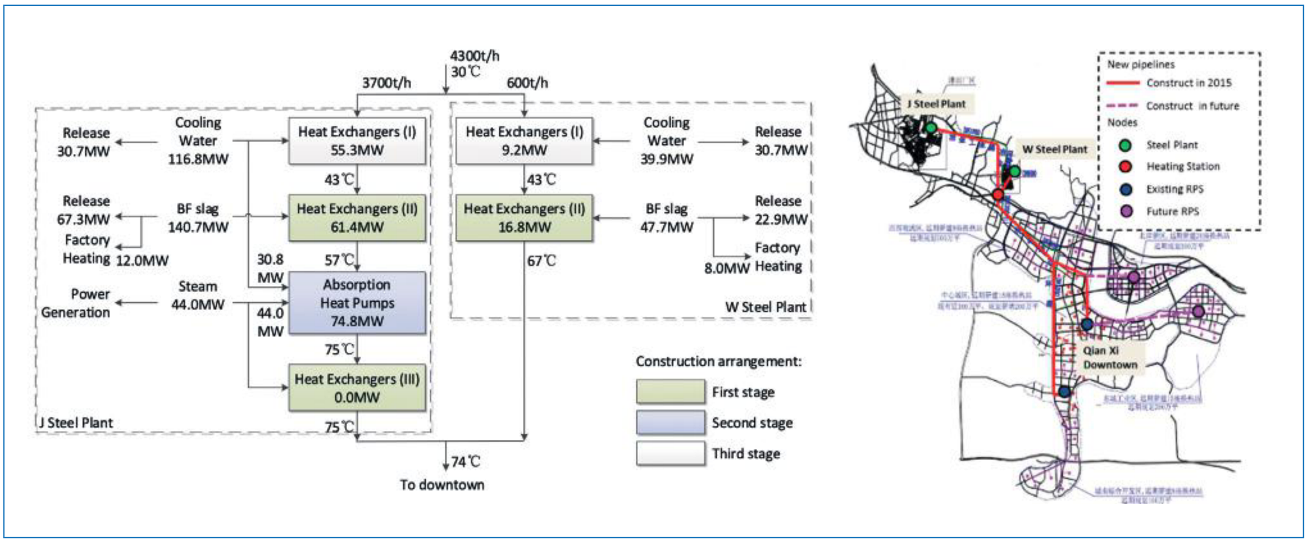

Fig 2.16. Heat recovery procedure and supply network. Provided by Tsinghua University with Permission for Reproduction

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 exiting 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_2 emissions per m^2). 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_2 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 H2, 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

AC	Air Conditioning
AC	Alternative Current
AI	Artificial Intelligence
BAPV	Building Attached PV
BECU	Building Electricity Consumption from Utilities
BIPV	Building Integrated PV
CCS	Carbon Capture and Storage
CDD	Cooling Degree Day
CHP	Combined Heat and Power
COP	Coefficient of Performance
DC	Direct Current (Continuous)
DEC	Direct Evaporative Cooling
EdF	Electricité de France
EJ	ExaJoule
EPC	Energy Performance Certificate
ESCO	Energy Service Company
GABC	Global Alliance of Buildings and Construction, Global ABC
GHG	Green House Gas
HVAC	Heating Ventilation Air Conditioning
IEC	Indirect Evaporative Cooling
IoT	Internet of Things
IPCC	International Panel on Climate Change
IT	Information Technology
LAC	Latin America and Caribbean (Countries)
LCA	Life Cycle Assessment
LED	Light Emitting Diode
LEEN	Learning Energy Efficiency Network
LPG	Liquefied Petroleum Gas
M&V	Measurement and Verification
MEPS	Minimum Energy Performances Standard
NBS	Nature Based Solution
NDC	National Determined Contribution
NPV	Net Present Value
O&M	Operation and Maintenance
PEDF	Photovoltaic Energy Storage, DC current and Flexibility (Buildings)
PEDF	Photovoltaic Energy storage, Direct Current, Flexibility (Buildings)
PLC	Power Line Current
PV	Photovoltaic
RESCO	Renewable Energy Service Company
RTS	Rooftop Solar PV
SCI	Smart City Index
SDG	Sustainable Development Goal
SDHW	Solar Domestic Hotwater System
SPV	Solar PhotoVoltaic
VRF	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

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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_2 from all fossil fuel combustion amounted to 33.5 Gt, the highest level ever, with 8% (2.65 $GtCO_2$) 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_2 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 $GtCO_2$.

The energy transition needed to lower carbon intensity is complex, risky and uncertain[1]. 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.

[1] 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-19th 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.*).

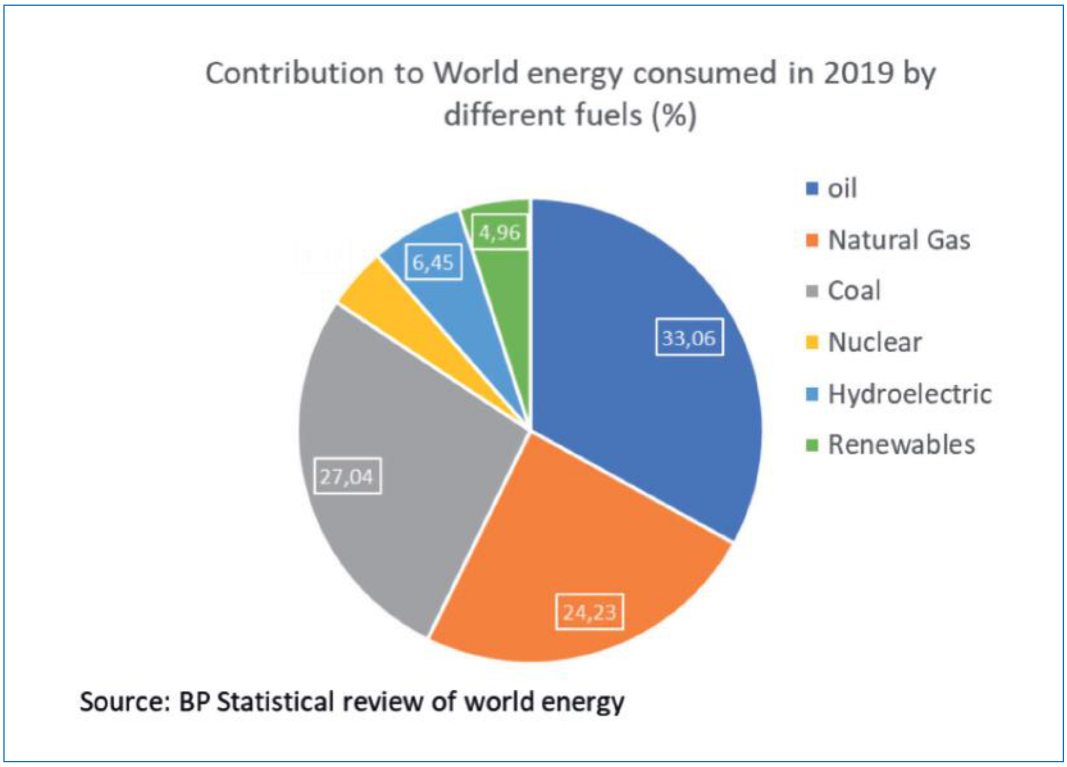


Fig. 3.1. Contribution to global PEC by different energy sources[2]

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.

[2] 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.*)[3].

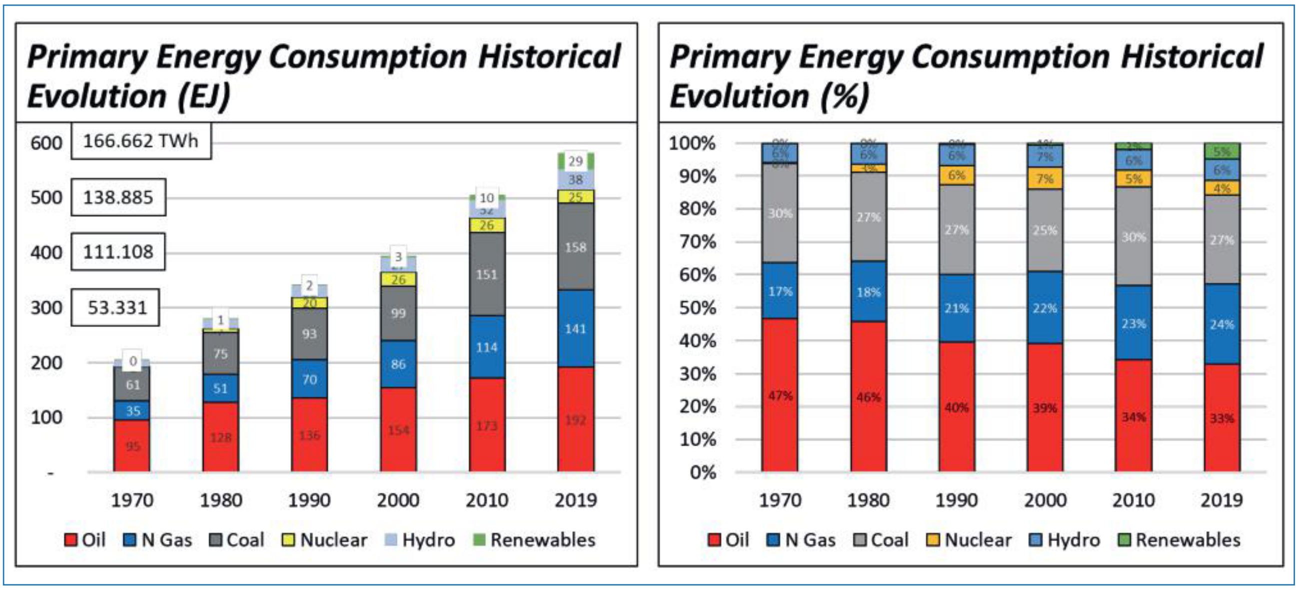


Fig. 3.2. Primary Energy Consumption (PEC)

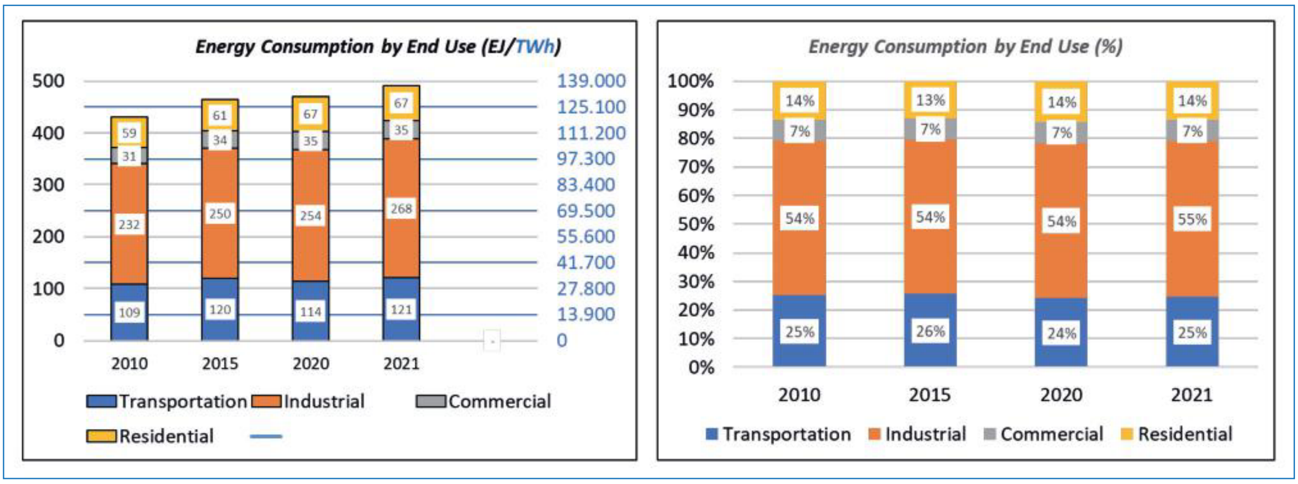
The demand growth rate for each primary energy source was different in each decade. Reasons include new technologies, price and demand changes and changes in GDP growth. Gas usage grew much faster than oil throughout this period, and it is projected to keep growing and reach a peak much later than oil. 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.

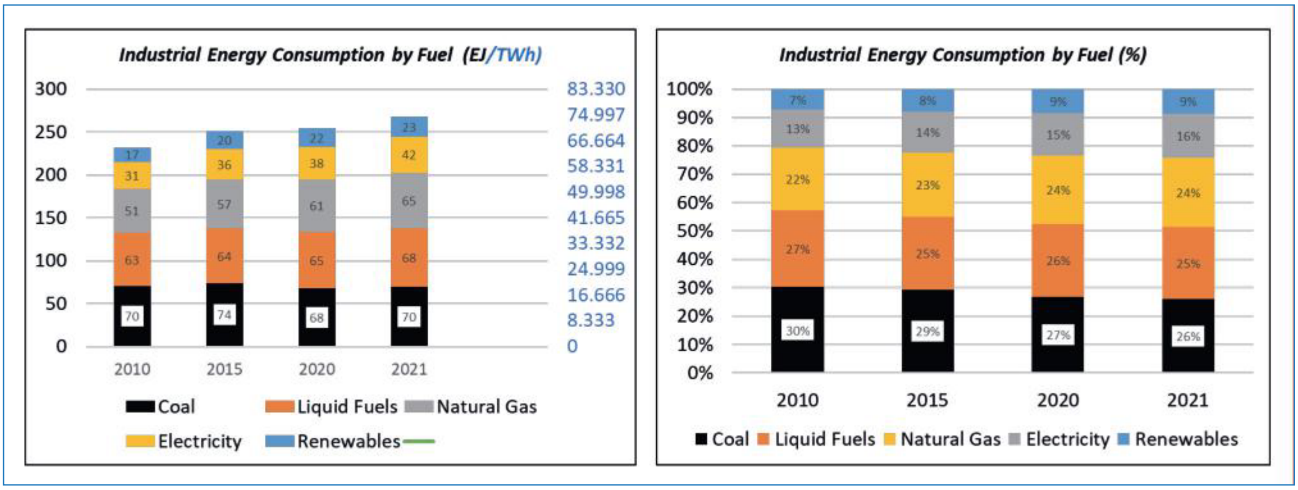
Energy demand by end use sectors is: industrial (54%), transport (25%), residential (14%) and commercial (7%) (cf. *Fig. 3.3.b.*).

3 U.S. Energy Information Administration-EIA - EIA 2021 International Energy Outlook https://www.eia.gov/outlooks/ieo/



(a) *(b)*

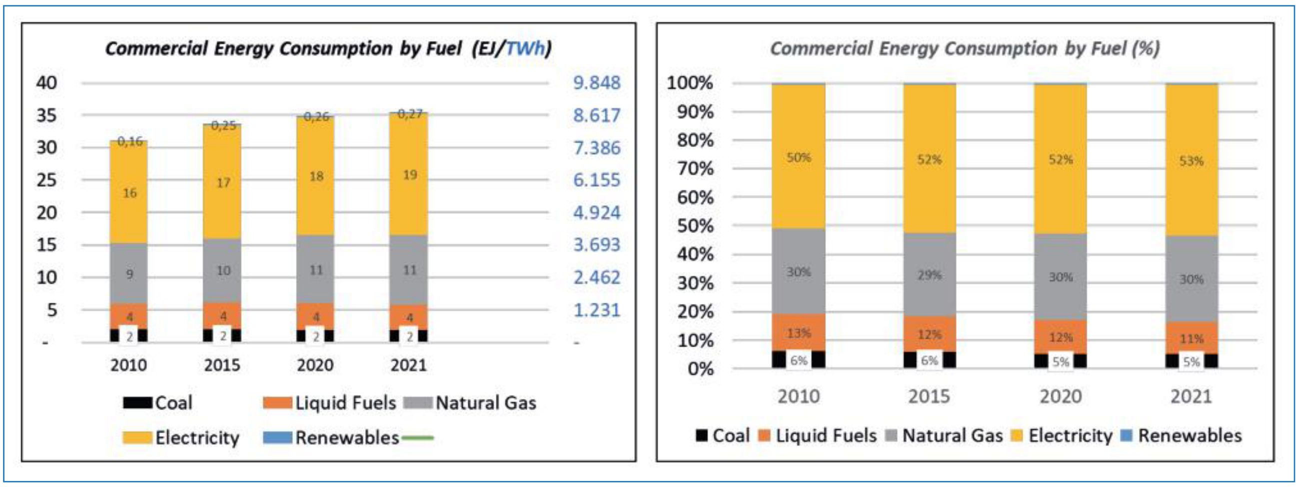
Fig. 3.3.a. and 3.3.b. Energy consumption by end use



(c) *(d)*

Fig. 3.3.c. and 3.3.d. Industrial energy consumption by fuel

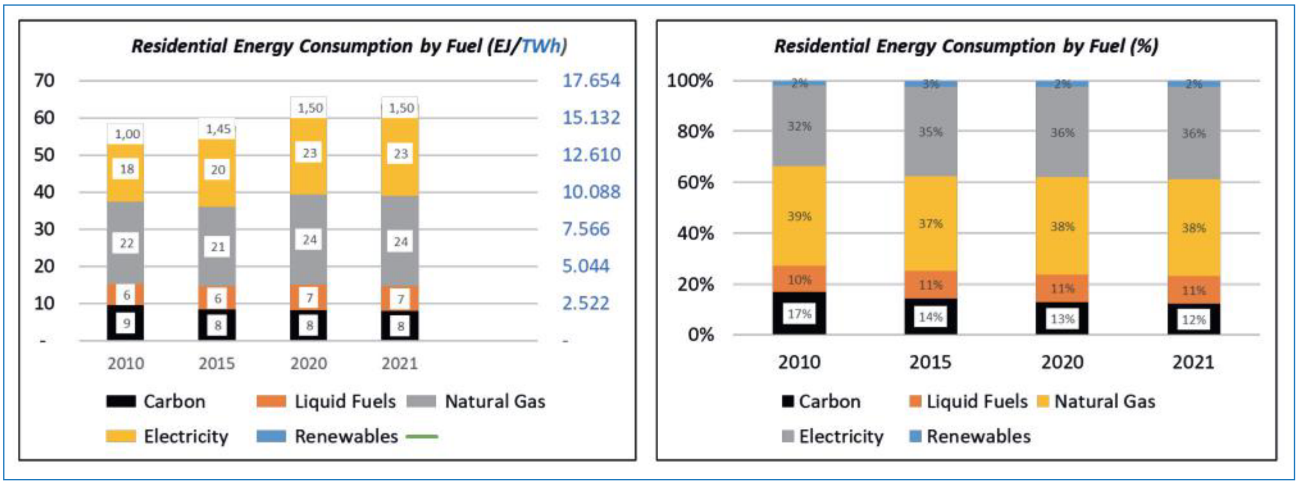
In 2021, coal (26%), oil (25%) and natural gas (24%) represented 75% of industrial demand for a total of 268 EJ. Worldwide 61% of disposable fossil fuels are used for electricity generation. Percentage-wise, the share of natural gas in electricity generation is growing, while oil and coal are declining.



(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[4]. 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.*)[5], 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.

4 IEA, Global Energy Review: CO_2 Emissions in 2021. https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2)
5 IEA, World Energy Outlook 2021

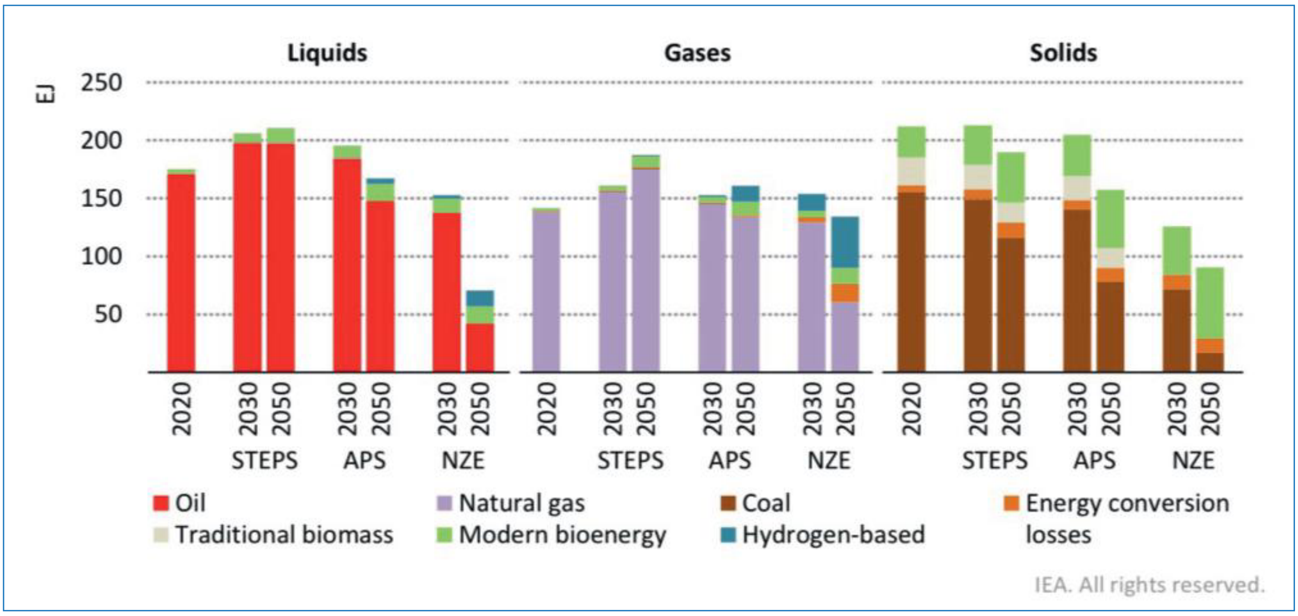


Fig. 3.4. Consumption of liquid, gaseous and solid fuels by scenario, IEA World Energy Outlook 2021 projections, p.213. Oil products consumption increases through 2050 in STEPS, and natural gas beyond 2050. Reproduced with Permission https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf

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[6].

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 21st 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.

6 IEA, The Future of Petrochemicals (2018). 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_2, 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. *See also*: https://link.springer.com/article/10.1007/s11367-020-01750-8

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[7]. 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_2 emissions[8]. The authors considered options for reducing GHG emissions related to Permian basin operations. They found that CO_2 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_2-based fracturing fluids. The authors concluded that much but not all of the Permian basin natural gas can be partially "decarbonised" if the CO_2 is sequestered in these ways.

7 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

8 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/acsengineeringau.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_2 emissions reached 33.5 $GtCO_2$ in 2021, about 0.22% higher than 2019 (IEA Global Energy Review)[3]. They accounted for about 67% of overall world greenhouse gas (GHG) emissions. Although CO_2 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_2 emissions

In 2021 the total global annual emissions of CO_2 from fuel combustion amounted to 33.5 $GtCO_2$[(4)], with 8% (2.65 $GtCO_2$) 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_2-e, was emitted[9]. These emissions (estimated to be 5.1 $GtCO_{2e}$ in 2021) account for as much as 12.5% of the world overall energy-related GHG emissions (40.8 Gt CO_{2e}) 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_2 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_2 emissions, while at the same time significantly improving energy efficiency.

[9] 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[10].
- 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_2 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_2 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 $kgCO_2$/MWh as a substitute for network electricity, and drive the reduction in CO_2 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.*)[10]. As methane has a global warming potential about 30 times higher than CO_2 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_2 equivalent (CO_{2e})[11], a figure equivalent to 90% of the energy emissions of the European Union in 2020. This is also comparable to the CO_2 emitted for petroleum production, transport, refining and processing (i.e. 2.65 $GtCO_2$).

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10 IEA: Curtailing Methane Emissions from Fossil Fuel Operations Oct. 2021. https://www.iea.org/reports/methane-tracker-2021

11 Energy Transitions Commission: Keeping 1.5 ºC Alive: Closing the Gap in the 2020s, Sept. 2021

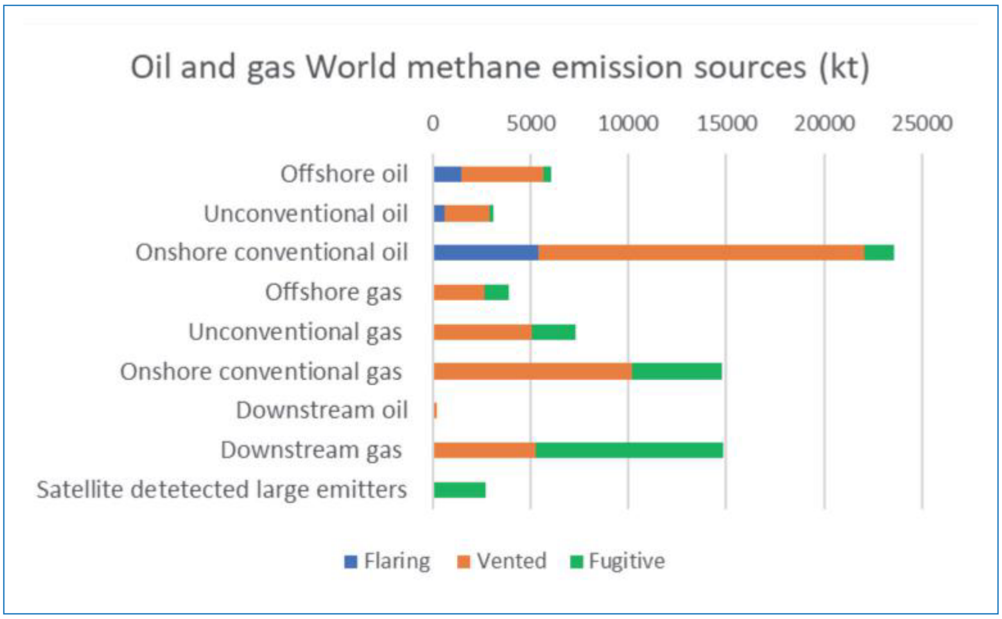

Fig. 3.5. IEA estimation of oil and gas methane emissions by source in 2020
Source of data for histogram: IEA 2021 Methane tracker. Reproduced with Permission
https://www.iea.org/reports/methane-tracker-2021

Anthropogenic methane emissions are the second largest cause of global warming behind CO_2 and seem to be growing at a faster rate than CO_2 in the atmosphere. Oil and gas production and supply are among their largest sources (*Fig. 3.6.*)[9]. 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.

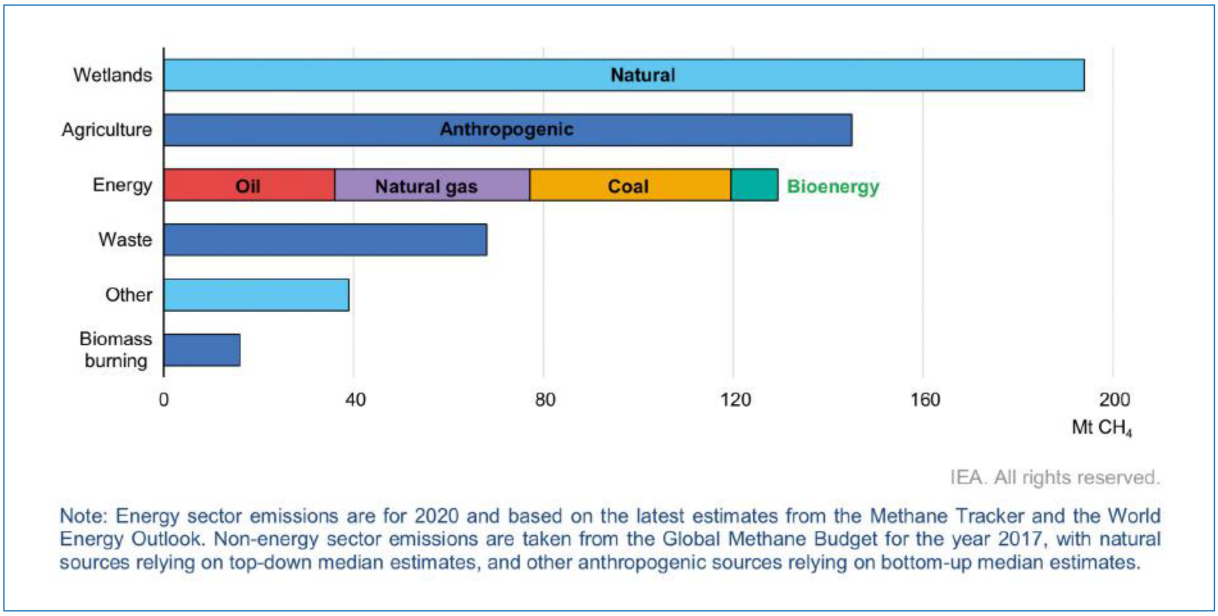

Fig. 3.6. World sources of methane emissions
IEA, "Curtailing Methane Emissions from Fossil Fuel Operations, Pathways to a 75% cut by 2030" Page 11 . Reproduced with Permission
https://iea.blob.core.windows.net/assets/ba5d143a-f3ab-47e6-b528-049f81eb31ae/CurtailingMethaneEmissionsfromFossilFuelOperations.pdf

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.

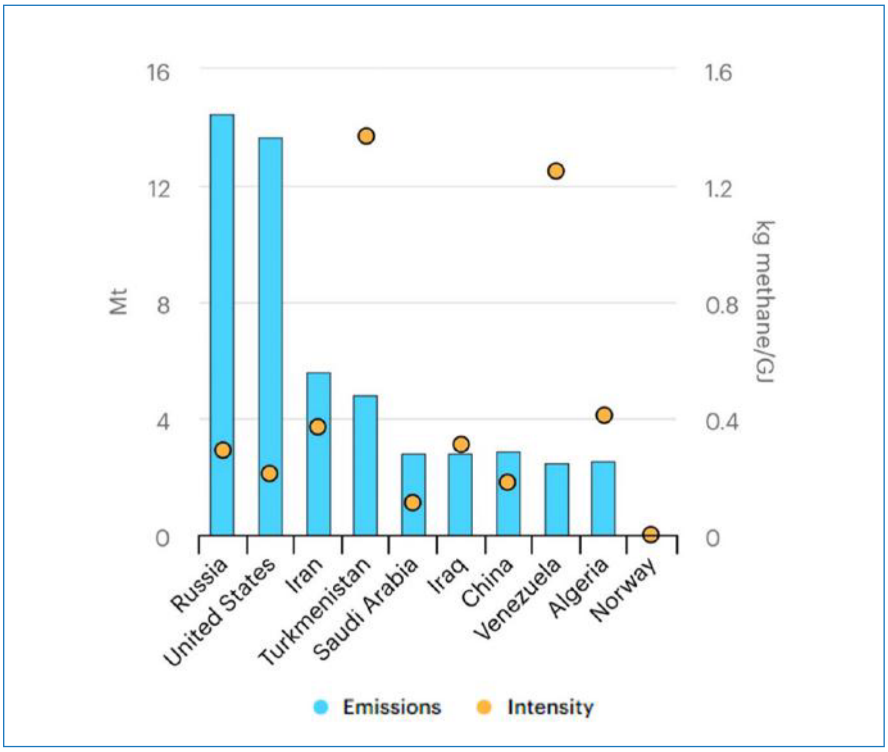

Fig. 3.7. Total methane emissions and methane intensity of production in selected oil and gas producers, 2021
Source: IEA, Methane Emissions from Oil and Gas Operations, Tracking report — September 2022, IEA. License: CC BY 4.0
https://www.iea.org/reports/methane-emissions-from-oil-and-gas-operations

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[9]. 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[12].

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)[13]

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)
Best Practice Guidance for Effective Methane Management in the Oil and Gas Sector – Monitoring, Reporting and Verification (MRV) and Mitigation, August 2019, Page 14, ©(copyright 2019) United Nations. Reproduced with the permission of the United Nations
https://www.globalmethane.org/documents/Best_Practice_Guidance_for_Effective_Methane_Management_in_the_Oil_and%20Gas_Sector_2019.pdf

12 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

13 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], 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[14].

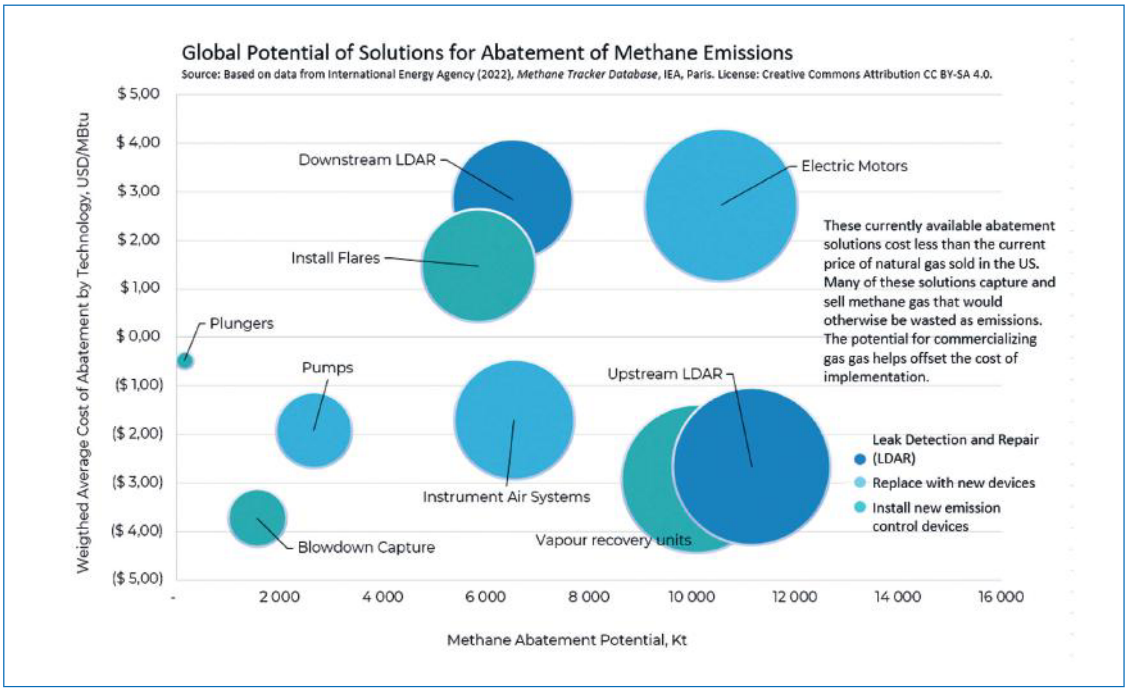

Fig. 3.8. Net-zero cost solutions for abatement of methane emissions
Produced by GEC with Permission to Reproduce. Kimberly L. Bell as contributor.
https://www.GECLP.com /

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).

[14] 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
1. Hydraulic fracturing & well completion	Green completion system	95%
2. Casing head venting from oil wells	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)	
3. Liquids unloading from gas wells	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	
	Install velocity tubing	
4. Glycol dehydrators	Install flash tank separator and optimise glycol circulation rates	Up to 90%
	Route flash tank (if present) and dehydrator regenerator vents to VRU for beneficial use	
	Route flash tank (if present) and dehydrator regenerator vents to flare (note: increase CO2 emissions)	Up to 98%
	Replacing by zero emissions (e.g. desiccant) dehydrators	100%
	Replace the gas assist lean glycol pump with an electric lean glycol pump	
	Reroute glycol skimmer Gas	Up to 95%
5. Natural gas driven pneumatic controllers and pumps	Replacement or retrofit to from high bleed to low bleed devices	Up to 97%
	Routing emissions to an existing combustion device or vapor recovery unit	Up to 95%
	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.	Up to 90%
	Replacement by zero emission options (electric or air driven)	100%
6. Wet-seal centrifugal compressors	Re-route gas at lower pressure to VRU, flare, or to a low-pressure inlet	Up to 95%
	Convert compressor wet seals to dry seals	Variable
7. Reciprocating rod-packing compressors	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%
8. Venting associated gas at upstream oil production facilities	Flaring without energy recovery instead of venting[88]	Up to 98%
	Capturing vent gas for gas utilization	up to 100%
	Install flare ignition systems[89]	Variable
9. Hydrocarbon liquid storage tank, loading & transportation, produced water discharge[90]	Reduce operating pressure upstream[91]	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%
	Hydrocarbon blanketing[92]	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.	
10. Equipment depressurization and blowdowns from pipelines and facilities	Use Isolation valves to minimize impact	Variable
	Re-direct gas into storage vessel (field), flare, or low-pressure header (fuel gas or gathering system)	
	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)	
	Install plugging equipment to shorten segment of pipeline involved in outage, Use isolation valves to minimize impact	
	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
11. Component and equipment leaks	Perform LDAR	Depends on frequency[93]
	Implement effective leak-prone pipe replacement program.	Variable
	Planned / carefully executed activities when excavating	
	Abandoned or suspended wells: Plug the well	
12. Incomplete combustion (including Associated petroleum gas (APG) flaring, engines, turbines, fired heaters)	Install automated air/fuel ratio controls	Variable/poor data
	Minimise the number of start-ups	
	Installing catalytic converters on gas fuelled engines and turbine	
	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[94]	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. ©(copyright 2019) United Nations. Reproduced with the permission of the United Nations
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.

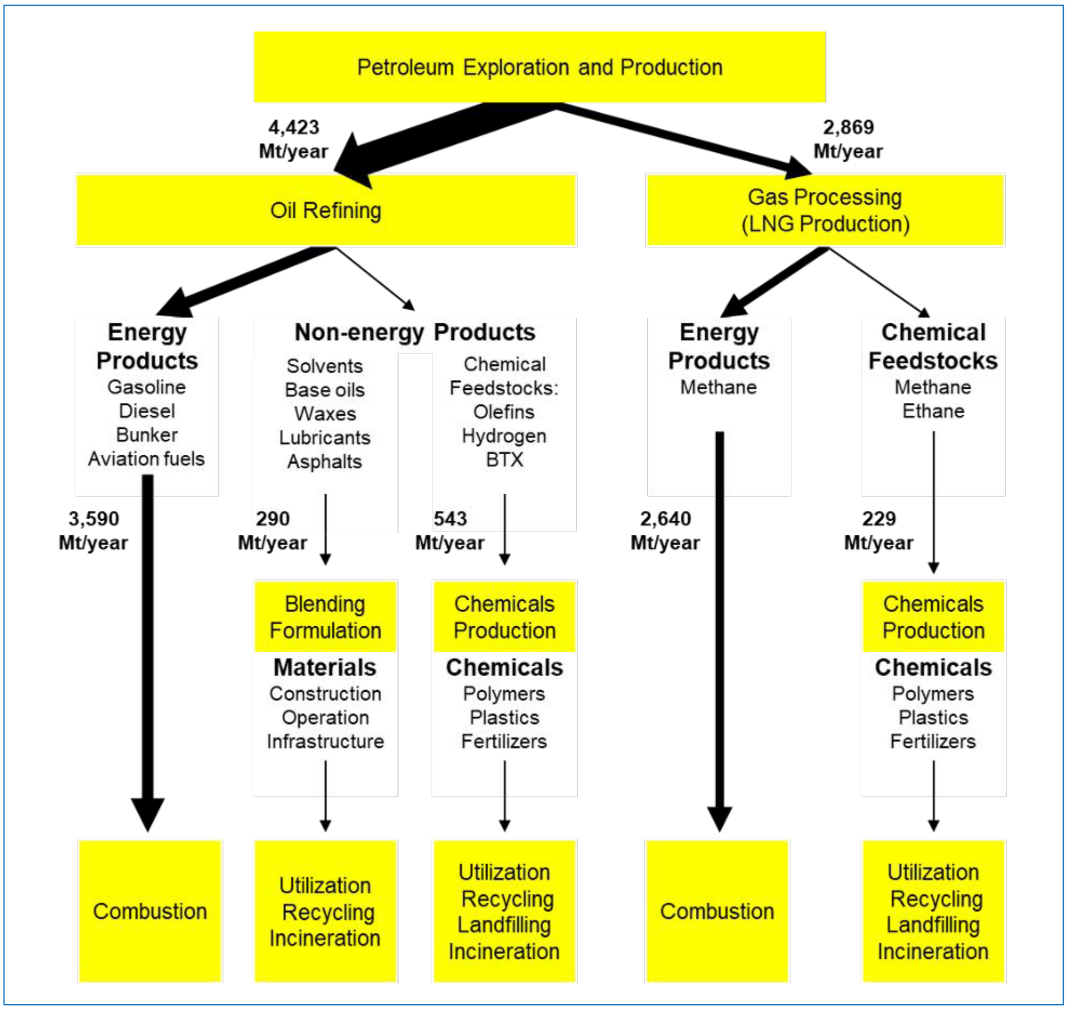

Fig. 3.9. The current petroleum industry, its principal products, and their disposition.
The width of the arrows symbolises the relative magnitude of what is produced

Five points to consider with respect to *Fig. 3.9.* are detailed below.

a. 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.

b. The global oil consumption of 4 423 Mt is equivalent to 90 million barrels per day (mbpd)[15, 16].

c. The natural gas consumption of 2 869 Mt is equivalent to 39 004 Gcm[13]

d. 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)[17].

e. The oil requirement for solvents, base oils, waxes, lubricants, and asphalts is 290 Mt.

[15] BP Statistical Review of World Energy (2021). http://www.bp.com/statisticalreview

[16] 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

[17] IEA, The Future of Petrochemicals (2018). https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The_Future_of_Petrochemicals.pdf

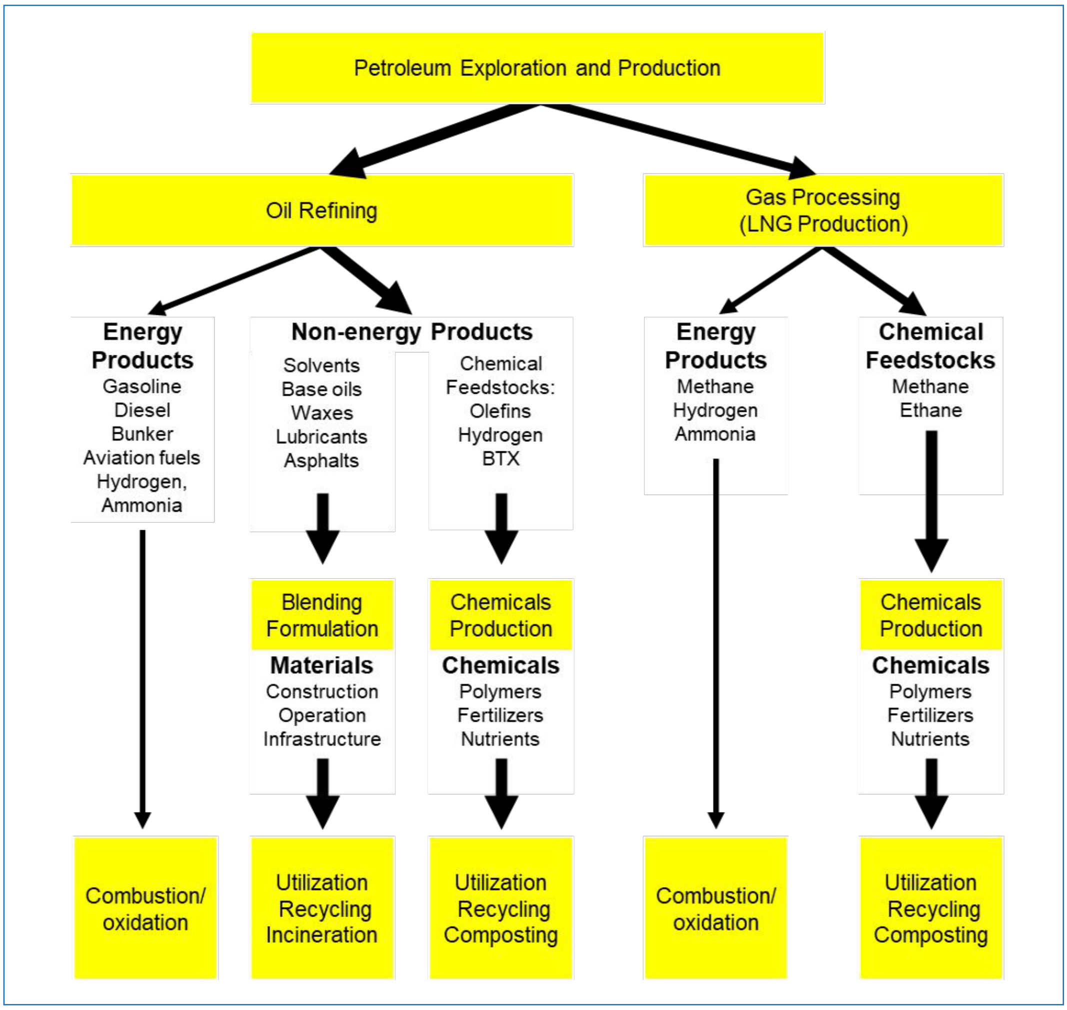

Fig. 3.10. The potential future petroleum industry, its principal products and their disposition.
The width of the arrows symbolises the relative magnitude of what is produced.

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[18], 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[19]. 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[20].

Examples of such schemes and technologies are currently being implemented in China and Saudi Arabia[21]. 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.

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[18] IEA, The Future of Petrochemicals (2018). https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The_Future_of_Petrochemicals.pdf

[19] 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

[20] DROP-IN BIOFUELS: The key role that coprocessing will play in its production, IAE Bioenergy: Task 39 (2019). https://task39.ieabioenergy.com/publications/

[21] 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_2 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.[22, 23, 24]

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[25].

[22] An Atlas. https://www.ipieca.org/resources/awareness-briefing/mapping-the-oil-and-gas-industry-to-the-sustainable-development-goals-an-atlas-executive-summary/

[23] https://www.worldbank.org/en/topic/climatechange/brief/3-things-you-need-to-know-about-climate-finance

[24] Energy Transition Outlook 2021. www.dnv.com/et; www.dnv.com

[25] https://discovery.ucl.ac.uk/id/eprint/10037715/3/Tomei_Manuscript%20-%20Energy%20and%20the%20SDGs_final.pdf

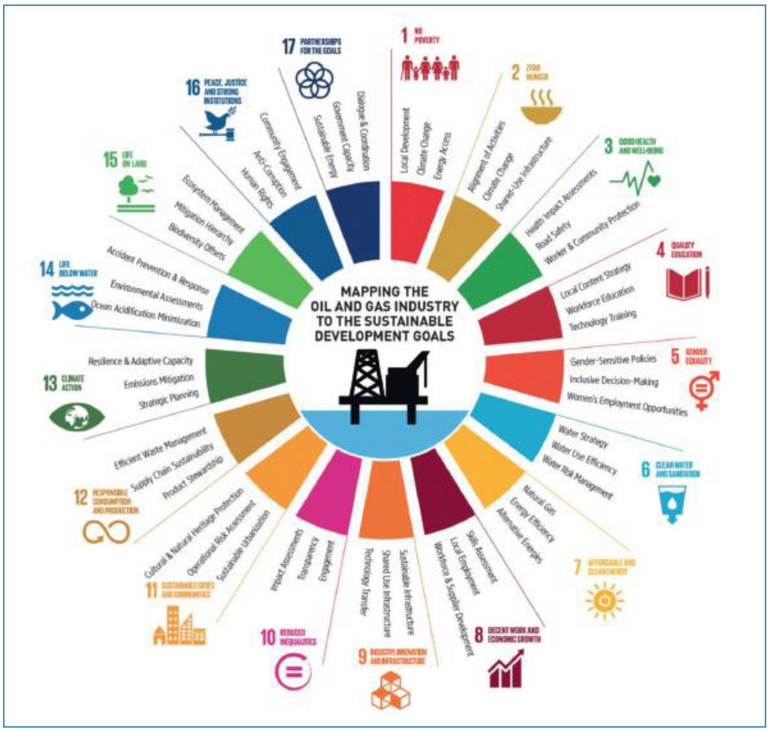

Fig. 3.11. Mapping the Oil and Gas Industry to the Sustainable Development Goals: An Atlas
IFC, IPIECA, UNDP Sustainable Development Goals, August 14, 2017, Page IX. Reproduced with Permission.
https://www.undp.org/publications/mapping-oil-and-gas-industry-sdgs-atlas?utm_source=EN&utm_medium=GSR&utm_content=US_UNDP_Paid-Search_Brand_English&utm_campaign=CENTRAL&c_src=CENTRAL&c_src2=GSR&gclid=Cj0KCQjwk5ibBhDqARIsACzmgLRuvyligH2PQLLwVSlXrY-ls-WyR8PwGb8XNUx_NIuj1xNF-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.[26, 27]

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.[28]

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_2 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.[29, 30]

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[31, 32]. 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

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26 The World Bank: Understanding Poverty. www.worldbank.org/climate

27 Waage, J. et al. Governing the UN sustainable development goals: interactions, infrastructures, and institutions. Lancet. Glob. Heal. 3, e251-2 (2015).

28 Brew-Hammond, A. Energy: The Missing Millennium Development Goal. 35–43 (2012). doi:10.1007/978-94-007-4162-1_3

29 https://www.worldbank.org/en/topic/climatechange/brief/3-things-you-need-to-know-about-climate-finance

30 Financing the Energy Transition; Energy Transition Outlook 2021. www.dnv.com/et; www.dnv.com

31 Nilsson, M., Griggs, D. & Visback, M. Map the interactions between Sustainable Development Goals. Nature 534, 320–322 (2016)

32 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[33]. All three partners have contributed people, experience and financial support.

4.3. Health

The World Health Organization[34] 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 disproportionally the cost, whether health or financial[35, 36].

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[37], 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.

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33 https://northernlightsccs.com/news/northern-lights-launches-company-dedicated-to-co2-transport-and-storage/

34 https://www.who.int/health-topics/climate-change#tab=tab_1 World Health Organization

35 https://www.worldbank.org/en/topic/climatechange/brief/3-things-you-need-to-know-about-climate-finance

36 Climate Change. https://www.who.int/health-topics/climate-change#tab=tab_1 World Health Organization

37 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_2 emissions per person in Sub-Saharan Africa are approximately equivalent to 1/20th of such emissions in North America; yet, developing countries[38] 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[39].

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[40], 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 word relies heavily on fossil fuels. 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_2.
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.

[38] https://dochub.com/goddy-igwe/pqb0g5YRqy9dN5DRJ2nx67/world-bank-report-1988-pdf?dt=5zDPHxidBLUCcWgZR7TH

[39] https://www.ft.com/content/6ee697a5-fe5c-473c-9b0c-9b68dd200288?accessToken=zwAAAYH_ZFFdkc9u5pel_lxHPNObDJto3SACiA.MEUCIQComTyeeWhVacNJyzCqszseSpVGTiSQBDzLSCWXcp-xCQIgO9-x41sU9fU-sTBT72LIdV-2ji35Ms4sUhvrKe4vBiA&sharetype=gift?token=3cd02569-d1cb-4039-8374-50774e6716f0

[40] 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_2 emissions

Although most CO_2 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_2 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_2 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_2, 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

AI	Artificial Intelligence
ALCA	Attributional LCA
APS	Announced Pledges Scenario
BECCS	Bioenergy with Carbon Capture
BTX	Benzene, Toluene, Xylene
CAETS	Council of Academies of Engineering and Technological Sciences
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CHP	Combined Heat and Power
CLCA	Consequential LCA
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DMS	Dynamic Matrix Control
EMS	Energy Management Systems
ETS	Emissions Trading System
EU	European Union
EV	Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HFC	Hydrofluorocarbon
IAM	Integrated Assessment Model
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
ILUC	Induced Land Use Change
IOGP	International Association of Oil and Gas Producers
IPIECA	International Petroleum Industry Environmental Conservation Association
LCA	Life Cycle Assessment
LDAR	Leak Detection And Repair
LED	Light Emitting Diode
LNG	Liquified Natural Gas
LUC	Land Use Change
MRV	Monitoring, Reporting and Verification
NG	Natural Gas
NGO	Non-Governmental Organisation
NZE	Net-Zero Emissions
OGCI	Oil & Gas Climate Initiative
PEC	Primary Energy Consumption
R&D	Research and Development
SDG	Sustainable Development Goal
SLCA	Societal LCA
STEPS	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)

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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_2 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_2) 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[1].

The chemical industry is the largest consumer of fossil hydrocarbons of all industrial sectors but ranks only third in terms of direct CO_2 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_2 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_2. 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_2.

The second purpose of fossil hydrocarbons is their direct use as fuel for process heating. In that case, the CO_2 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_2 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_2.

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.

[1] 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[2], 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)[3] 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[4].

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.

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2 IEA: Chemicals tracking report, Nov. 2021. https://www.iea.org/reports/chemicals

3 IEA: The future of petrochemicals, towards more sustainable plastics and fertilizers (2018). https://www.iea.org/reports/the-future-of-petrochemicals

4 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.

a. 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.
b. 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.
c. 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.*

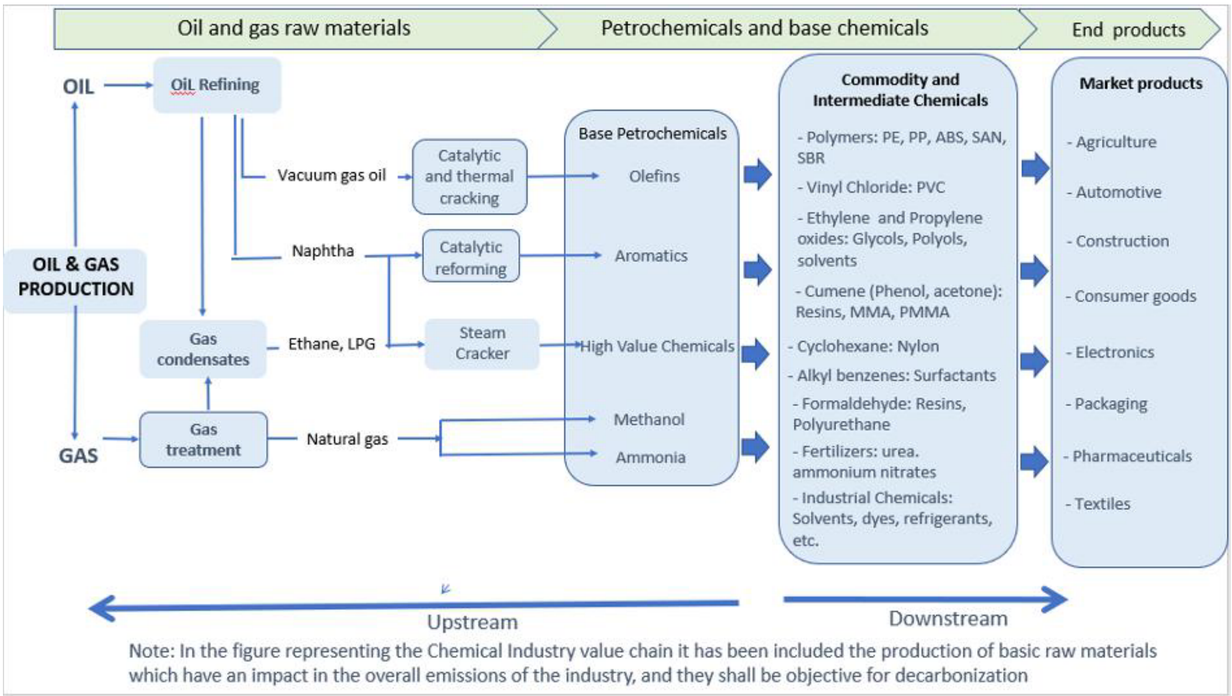

Fig. 4.1. The chemical industry value chain [1]
Data source for right-hand part of diagram:
https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The_Future_of_Petrochemicals.pdf

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[5], 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_2 emissions. Since the selection of feedstock plays a crucial role in reducing CO_2 emissions for ethylene production, it is of prime importance to maximise the use of ethane in ethylene production so as to reduce process CO_2 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[6] 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.

5 Burdick, Donald L., Leffler, W.L., Petrochemicals in nontechnical language, 4th Ed., PennWell Corporation, Tulsa Oklahoma. www.pennwellbooks.com 2009045189. ISBN 978-1-59370-216-8

6 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[7].

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_2 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_2 emissions when ethylene is being produced.
- Employ green hydrogen and captured CO_2, 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.

[7] Burdick, Donald L., Leffler, W.L., Petrochemicals in nontechnical language, 4th Ed., PennWell Corporation, Tulsa Oklahoma. www.pennwellbooks.com 2009045189. ISBN 978-1-59370-216-8

5. Ammonia

Ammonia production accounts for about 1.0% of global annual CO_2 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[8]. 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_2 and 823 kg of N_2 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%[9]. The production of ammonia thus generates CO_2 emissions: of 1.6 tCO_2/tNH_3 when natural gas is employed for hydrogen generation, 3.0 tCO_2/tNH_3 when fuel oil is employed, and 3.8 tCO_2/tNH_3 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[10].

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.

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8 Global ammonia production by country 2020 | Statista Global ammonia production by country 2020 | Statista

9 https://cen.acs.org/environment/green-chemistry/Industrial-ammonia-production-emits-CO2/97/i24

10 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[11], 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)[12], 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_2/tNH3. Switching the hydrogen production method from methane to electrolysis of water reduces CO_2 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[13].

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.

11 Ammonia: zero-carbon fertiliser, fuel and energy store Issued: February 2020 DES5711, ISBN: 978-1-78252-448-9 © The Royal Society

12 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/

13 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_2 per year, and account for 10% of all the emissions of the chemical sector[16]. 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[14]. According to current trends, the global production of methanol could reach 550 Mt per year by 2050[15].

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[16]. MTO production is estimated to increase by 7% annually[17].

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 (SOx, NOx, 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%[18].

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_2 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[19].

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-

14 https://www.methanol.org/wp-content/uploads/2016/07/IHS-ChemicalBulletin-Issue3-Alvarado-Jun16.pdf

15 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf

16 http://www.cchem.berkeley.edu/molsim/teaching/fall2009/mto/background.html

17 https://www.methanol.org/wp-content/uploads/2016/07/IHS-ChemicalBulletin-Issue3-Alvarado-Jun16.pdf

18 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf

19 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_2 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_2 net emissions while also reducing the global reliance on fossil fuels[20]. 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[21].

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[22].

According to the IEA[23], 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.

20 Tuan-Dung Hoang, Nhuan Nghiem(2021), Recent Developments and Current Status of Commercial Production of Fuel Ethanol, Fermentation 2021, 7(4), 314

21 Global Ethanol Production by Country or Region. Available online: https://afdc.energy.gov/data/10331/ (accessed on 10.02.2022).

22 https://www.nsenergybusiness.com/features/top-biofuel-production-countries/

23 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. Liquified 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_2 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_2 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_2 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_2 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_2 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

BTX	Benzene, Toluene and Xylenes
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CPI	Chemical Process Industries
FCC	Fluid Catalytic Cracking
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HBS	Haber-Bosch Synthesis
HVC	High Value Chemicals
ICE	Internal Combustion Engine
IEA	the International Energy Agency
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MTBE	Methyl tert-Butyl Ether
MTO	Methanol to Olefins
SOFC	Solid Oxide Fuel Cell
TLE	Transfer Line Exchanger
TRL	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, Argenina

Kearsley Elisabeth, South Africa

Perry Brian, South Africa

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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_2. 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_2. 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 corporation 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_2 emission in cement manufacturing (as indicated *Fig. 5.1.*), as this process produces most of the industry's CO_2 emissions. Neither quarrying nor the production of concrete shall be discussed.

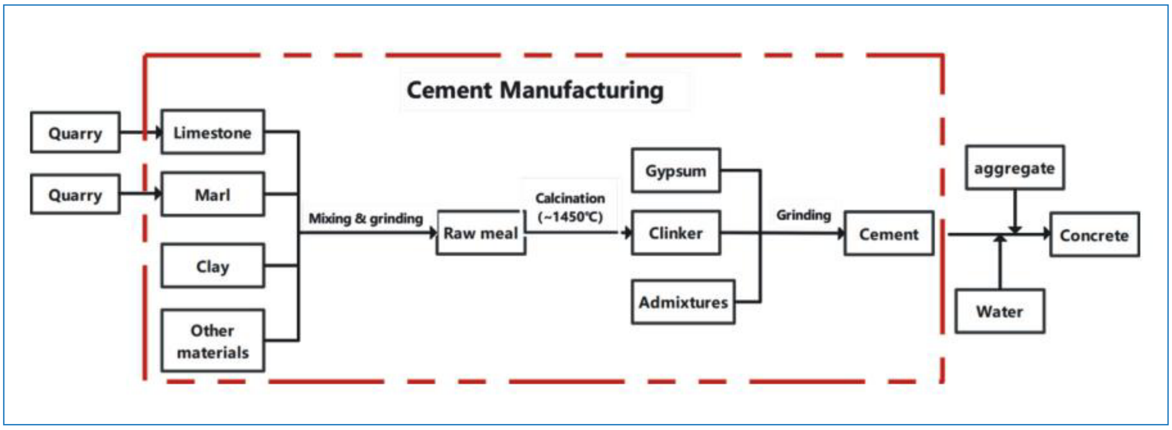

Fig. 5.1. The research scope of this report is cement manufacturing

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%.

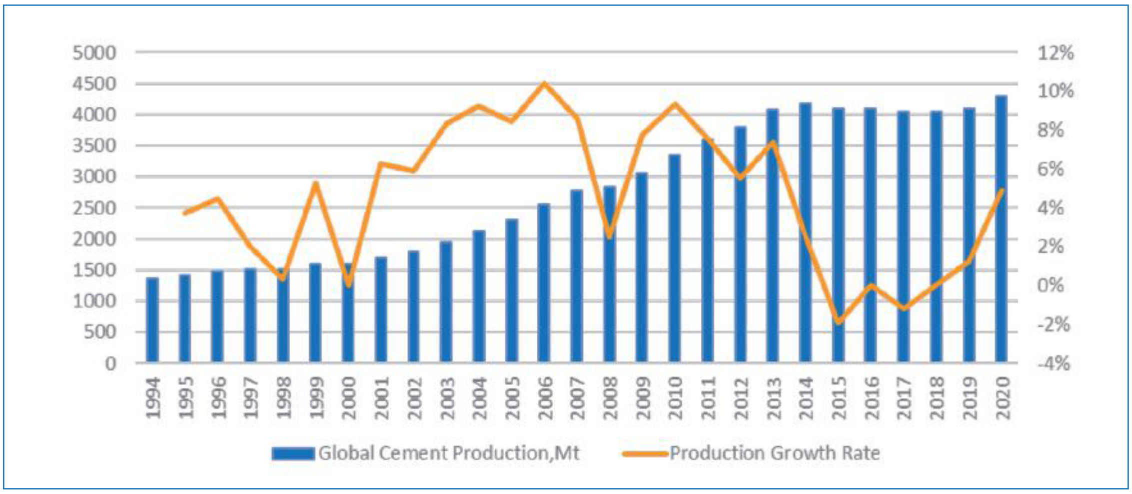

Fig. 5.2. Global cement production and production growth rate[1]

[1] 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_2 in 2020[2].

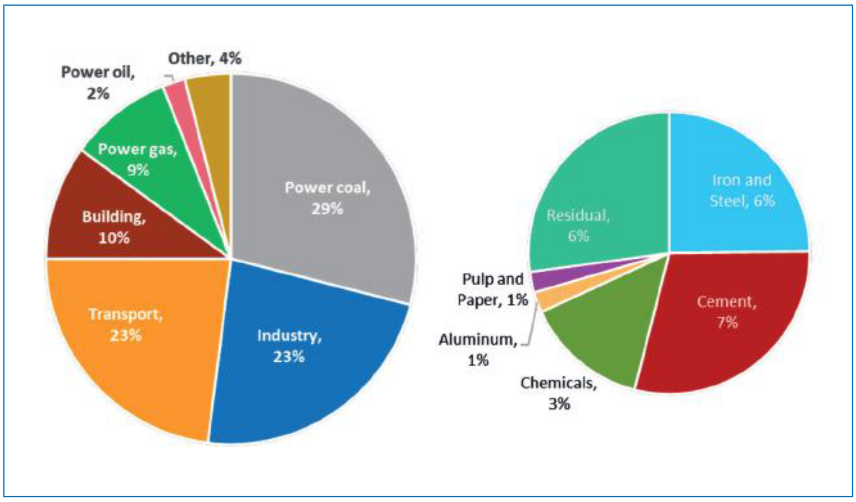

Fig. 5.3. Global energy-related CO_2 emissions by sector[3]

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.

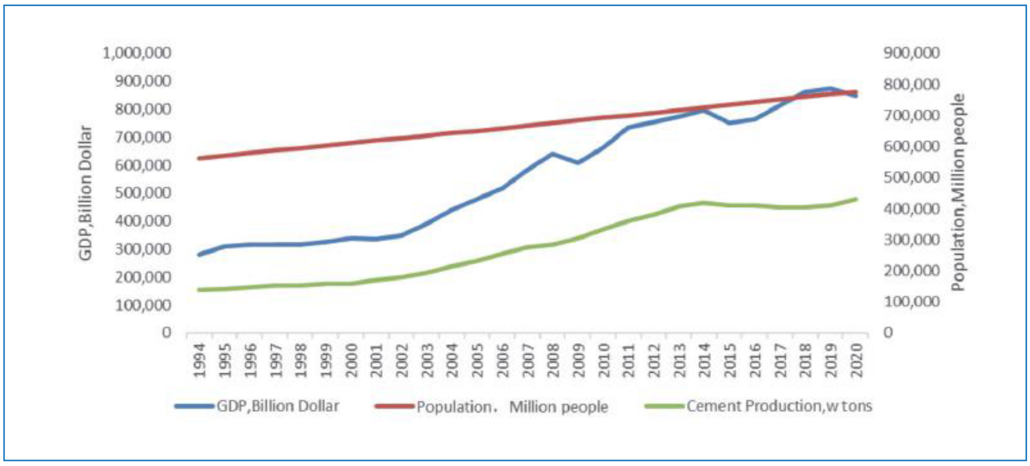

Fig. 5.4. Principal characteristics of the global cement industry[4, 5, 6]

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.*.

2 (2021),Cement tracking report (https://www.iea.org/reports/cement)

3 IEA(2021),Global energy-related CO_2 emissions by sector
left: https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-by-sector, License: CC BY 4.0
right: https://www.iea.org/reports/industry, License: CC BY 4.0

4 World Bank, Global population

5 U.S. Geological Survey, Cement Statistics and Information (https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information)

6 International Monetary Fund,Global GDP

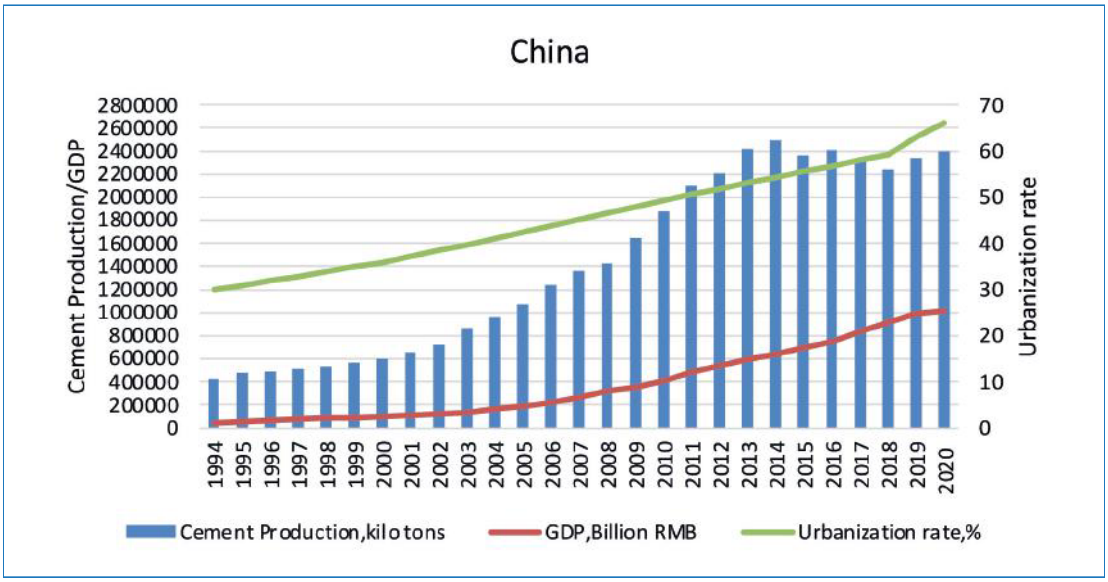

Fig. 5.5. Principal characteristics of the cement industry in China[7, 8]

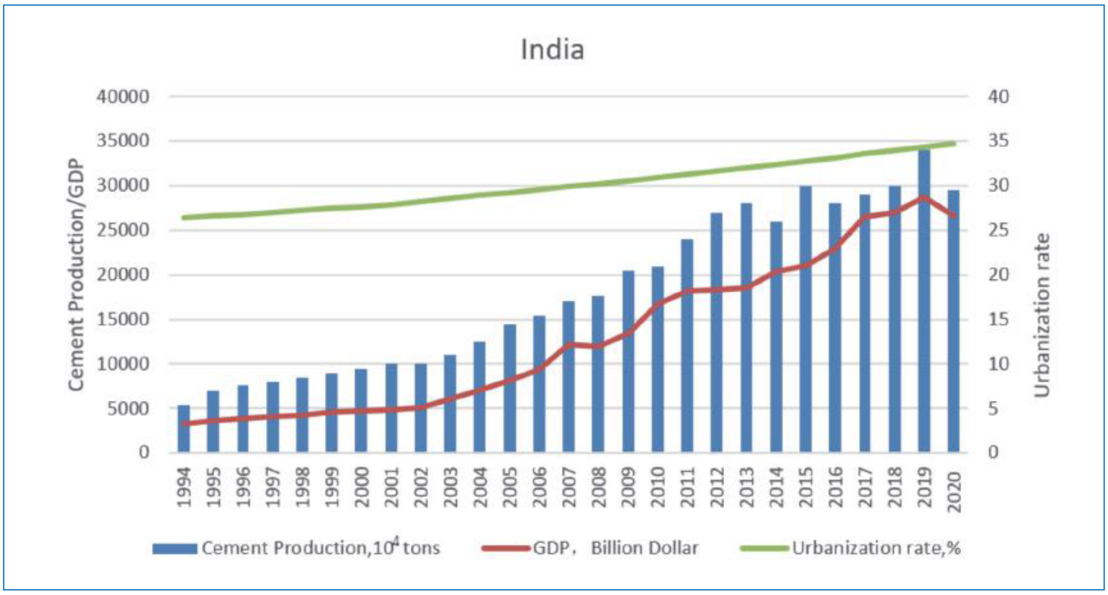

Fig. 5.6. Principal characteristics of the cement industry in India[9, 10]

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.*.

7 National Bureau of Statistics of China, China population

8 U.S. Geological Survey, Cement Statistics and Information (https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information)

9 Indian Bureau of Statistics,GDP & population statistics

10 U.S. Geological Survey, Cement Statistics and Information (https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information)

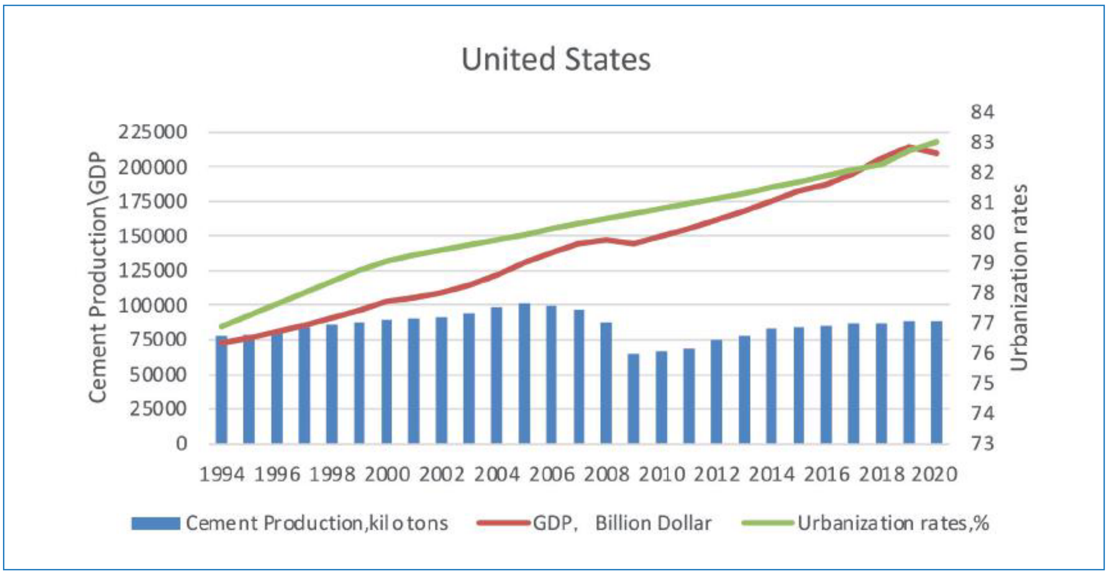

Fig. 5.7. Principal characteristics of the cement industry in United States[11, 12]

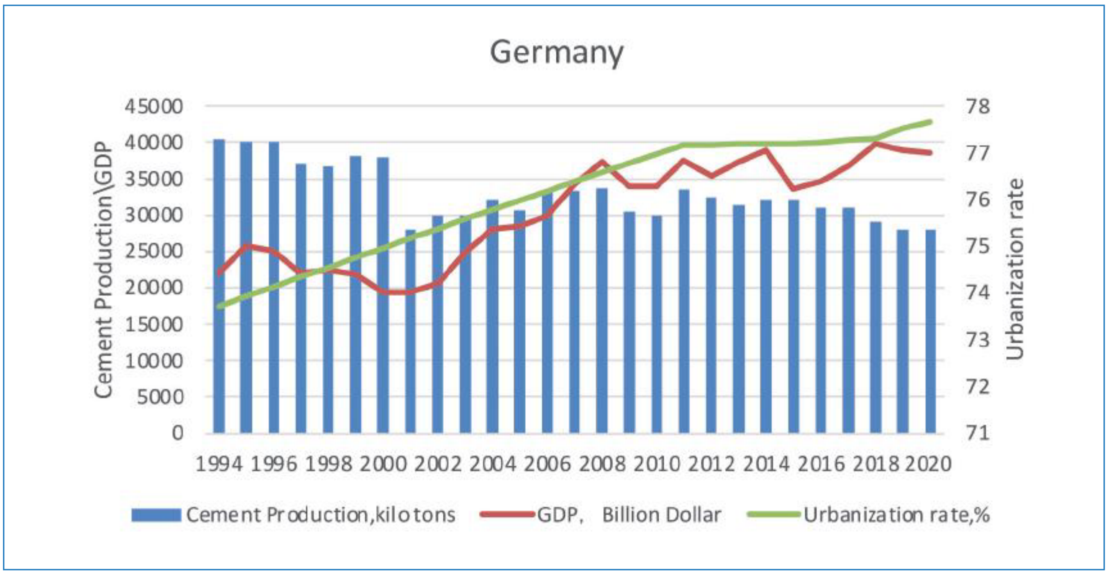

Fig. 5.8. Principal characteristics of the cement industry in Germany[13, 14]

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.

11 U.S. Bureau of Economic Analysis, GDP & population statistics

12 U.S. Geological Survey, Cement Statistics and Information (https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information)

13 Eurostat,GDP & population statistics

14 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_2 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_2 emissions from cement production being purely process related, the industry is not only a source of combustion-related CO_2 emissions, but also the largest source of process-related CO_2 emissions in any industrial sector. The process in question is the calcination process, which contributes about 50% of CO_2 emissions, while the combustion of solid fuels contributes about 40%. The remaining CO_2 (about 10%) is emitted during the transport of raw material and some other production processes that consume electric power[15].

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.*.

[15] Mikulčić, H, Vujanović, M, Duić, N. 2013. Reducing the CO_2 emissions in Croatian cement industry. Appl. Energy 101, 41-48. doi: 10.1016/j.apenergy.2012.02.083

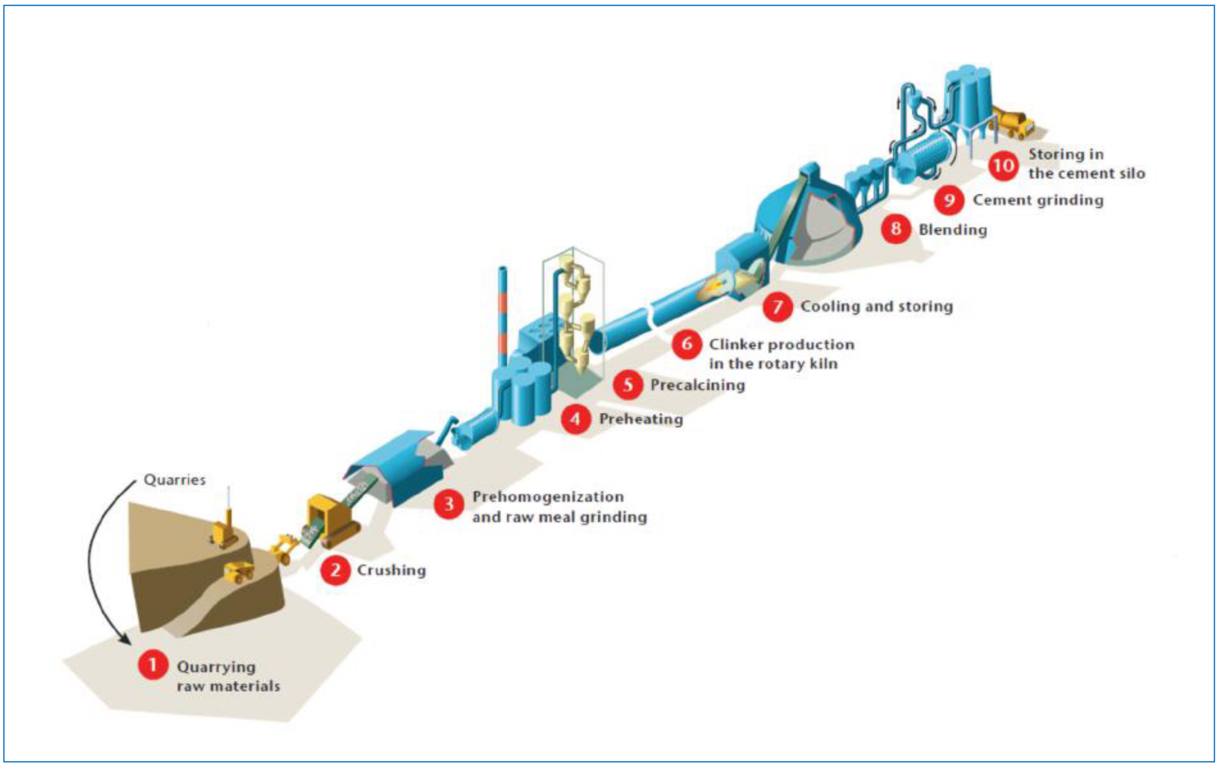

Fig. 5.9. Cement manufacturing process[16]

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_2 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[17].

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.*.

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[16] 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

[17] Mikulčić, et al., 2016

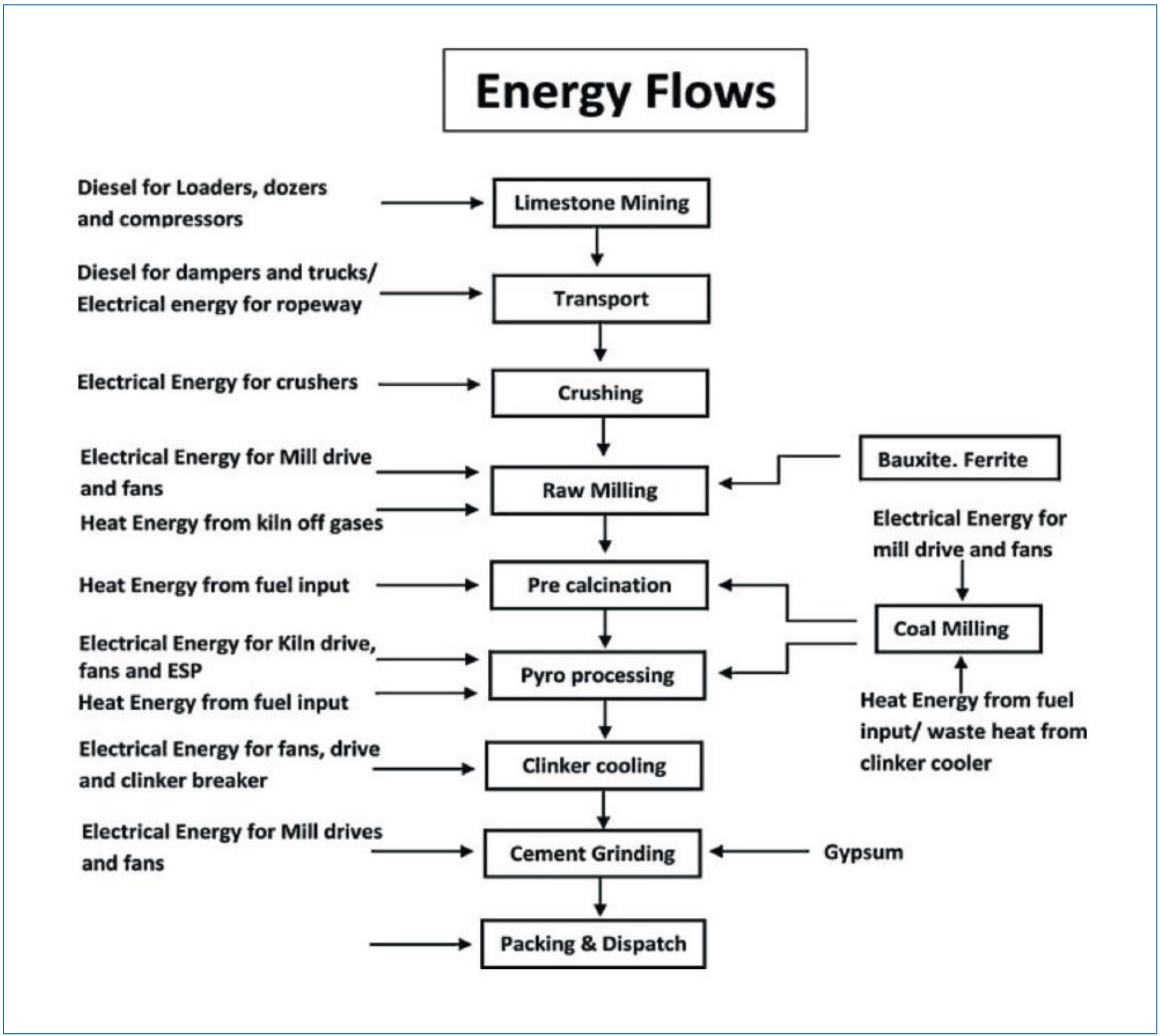

Fig. 5.10. Cement manufacturing process energy flows[18]. CCC RightsLink License N° 5471390938086
https://www.sciencedirect.com/science/article/pii/S1364032111000207

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.

[18] 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[19]	0.76%	58.9[20]	1.37%
Other (rounded)	472	12.8%	Not Available	-
World total (rounded)	3 700	-	4 300	-

Table 5.1. Global cement production[21]

The importance of cement production in these developing economies can also be observed when comparing the annual CO_2 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_2 emissions[22]. Whereas in China, the largest cement producing country and largest emitter of GHG emissions in the world, 15% of total CO_2 emissions are related to cement production[23].

19 Cement Production in Nigeria,Mmemek-Abasi Etim, Atmosphere,2021.9

20 Cement Production in Nigeria,Mmemek-Abasi Etim, Atmosphere,2021.9

21 Statista, 2021. https://www.statista.com/statistics/267364/world-cement-production-by-country/ for Major countries in worldwide cement production from 2010 to 2020

22 Pardo N, Moya JA, Mercier A. 2011. Prospective on the energy efficiency and CO_2 emissions in the EU cement industry. Energy. 36, 3244-3254. doi: 10.1016/j.energy.2011.03.016

23 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.

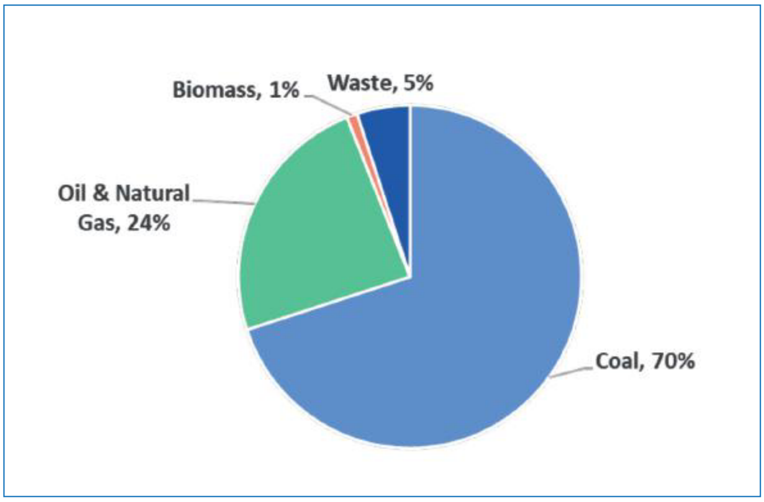

Fig. 5.11. Fuel mix in the cement industry[24]

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.

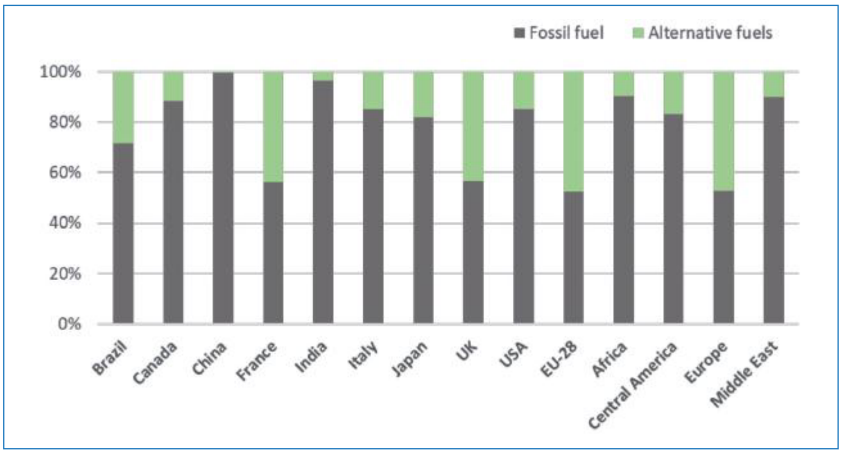

Fig. 5.12. Regional thermal energy mix ratio in the cement industry[25]

[24] Source of data: IEA(2018),Technology Roadmap-Low Carbon Transition in the Cement Industry, Page 29, CC BY 4.0 https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry

[25] Source of data: Thermal specific energy consumption per tonne of clinker in selected countries and regions, 2018 – Charts – Data & Statistics - IEA, CC BY 4.0 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_2 Emission in the cement production

2.4.1. CO_2 emission intensity of the cement production

As already stated, in the cement production process, nearly 90% of CO_2 emitted results from two thermochemical processes. Taking China's cement industry as an example, *Table 5.3* displays energy consumption, emission intensity and CO_2 emission at each of these steps

Item	Unit consumption	Emission factor	Emission of CO_2	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
Total emission	**562.7~615.5 kgCO_2/ton cement**				

Table 5.3. CO_2 emission from cement production in China[26]

[26] 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_2 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_2 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_2 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_2 emission intensity.

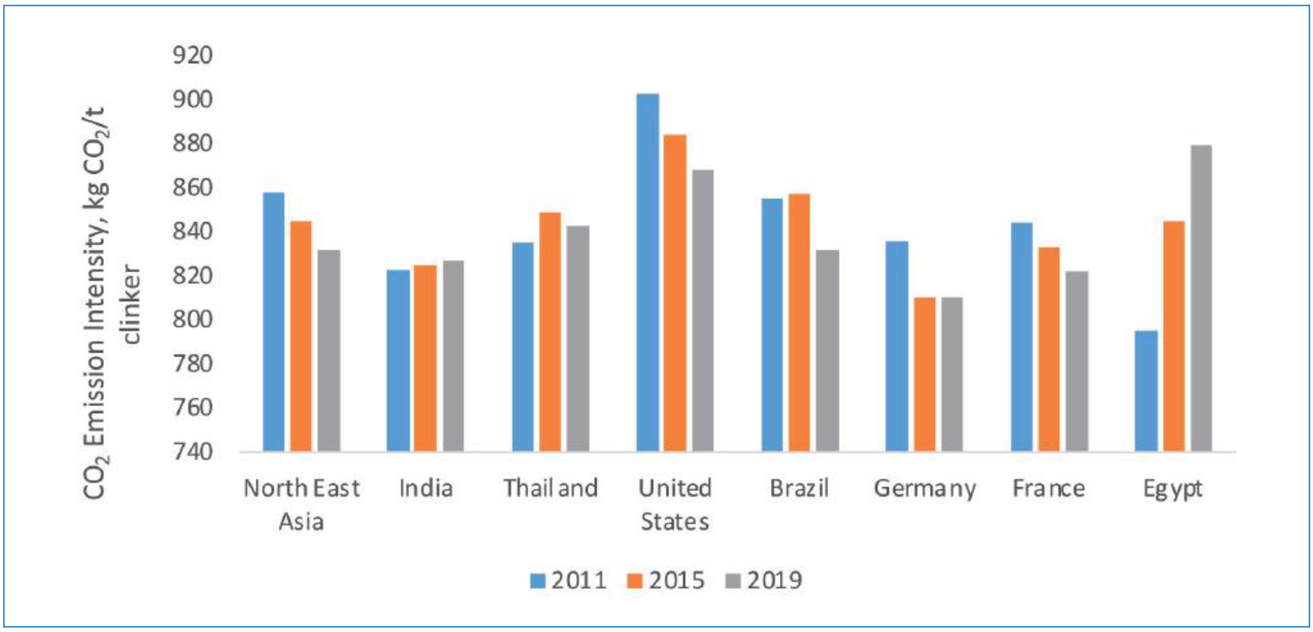

Fig. 5.13. CO_2 emission intensity of clinker for different countries[27], Data source: GCCA, Gross CO_2 emissions–Weighted average excluding CO_2 from on-site power generation –Grey clinker. https://gccassociation.org/sustainability-innovation/gnr-gcca-in-numbers/ Reproduced with Permission

[27] Data source: GCCA GNR Data base, Gross CO_2 emissions–Weighted average excluding CO_2 from on-site power generation–Grey clinker.

3. Technologies for decarbonisation

Various technologies include digital solutions to support automation. In the cement industry, process control, reductions in fuel consumption, production increases and product quality improvements are carried out.

3.1. Energy efficiency improvements

The energy efficiency of cement can progress through technological upgrades and improvements throughout the whole cement production process, as shown in *Fig. 5.14.*.

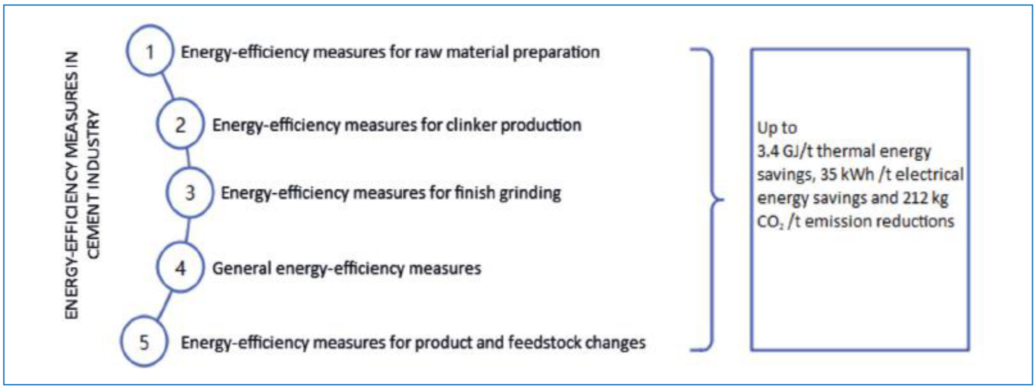

Fig. 5.14. Overview of energy efficiency measures for the cement industry[28].
Units: 3.4 GJ/t or 0.94 MWh/t. CCC RightsLink License N° 5471391509900
https://www.sciencedirect.com/science/article/abs/pii/S1364032112005977

- The progressive replacement of the wet process with the dry method was the first step taken to achieve energy efficiency and this has been gradually implemented globally. The energy specifically used in the production of clinker has been thus been reduced from 5.29 GJ/t to 3.40 GJ/t.
- The measures to make energy savings and reduce GHG emissions in the dry process are shown in *Fig. 5.15.*. These mainly include: advanced raw meal grinding, separate raw material grinding, waste heat recovery system (WHRS), etc.

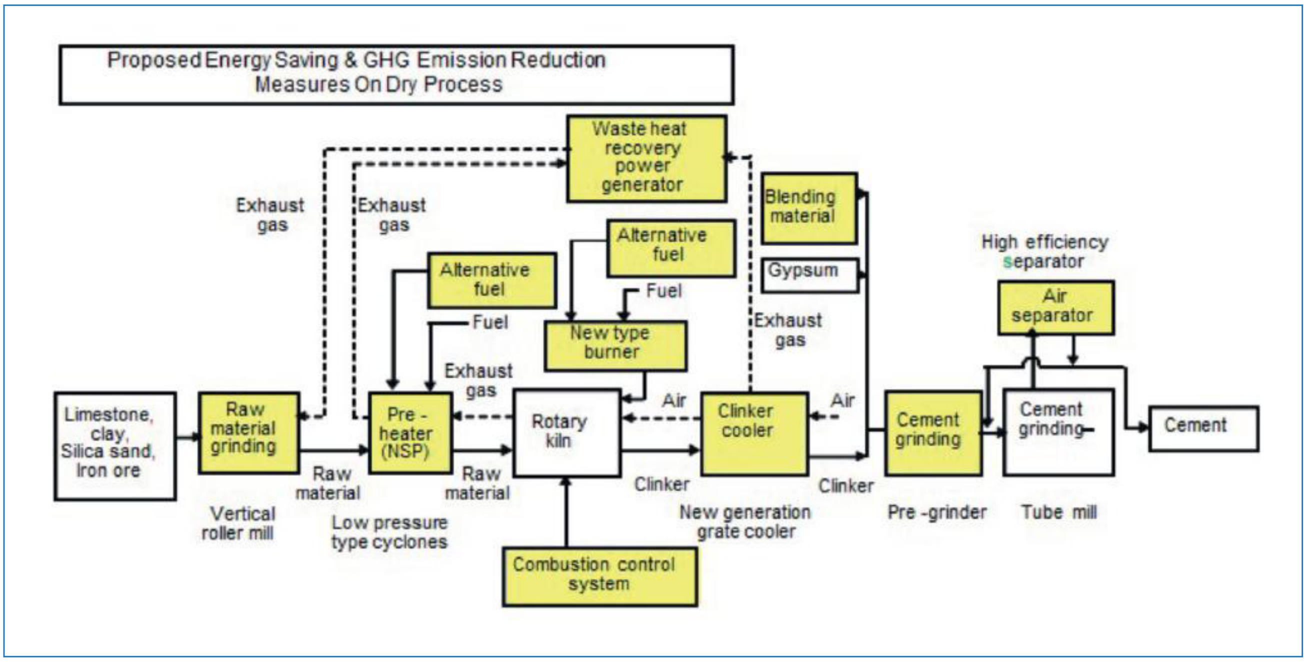

Fig. 5.15. Energy saving & GHG emission reduction measures on dry process[29]
Taiheiyo Engineering Corporation, Japan. Reproduced with Permission

[28] N.A. Madlool, R. Saidur, N.A. Rahim, M. Kamalisarvestani, An overview of energy savings measures for cement industries, Renewable and Sustainable Energy Reviews, 2013, 19:18-29.sciencedirect.com

[29] http://gec.jp/jcm/projects/p_archive/13fs_mgl_02/

- 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.[30] 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.

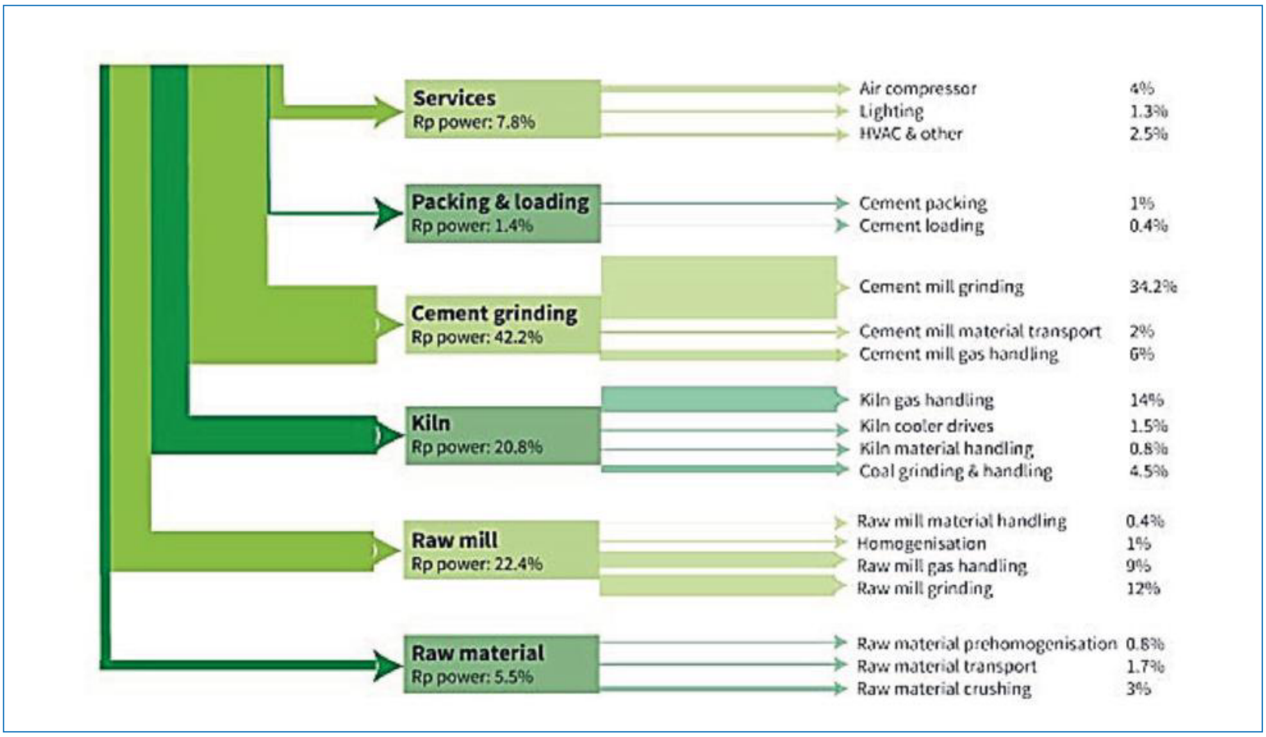

Fig. 5.16. Breakdown of electrical energy consumption at a typical cement plant[31]. Reproduced with Permission

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.

30 http://cadd.mapei.com/wp-content/uploads/2016/03/2010-09-Mapei_Paper_ICR_Sept-2010.pdf

31 The Cement Plant Environmental Handbook (2nd 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.*.

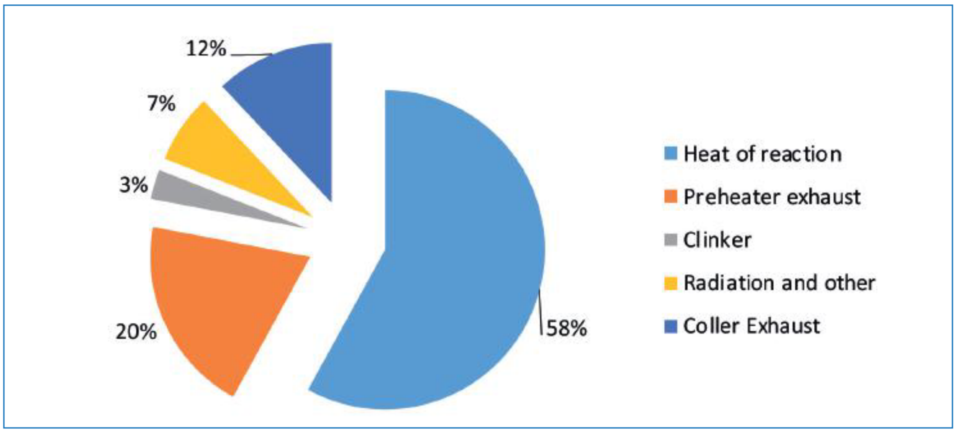

Fig. 5.17. Waste heat sources in cement plant

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.

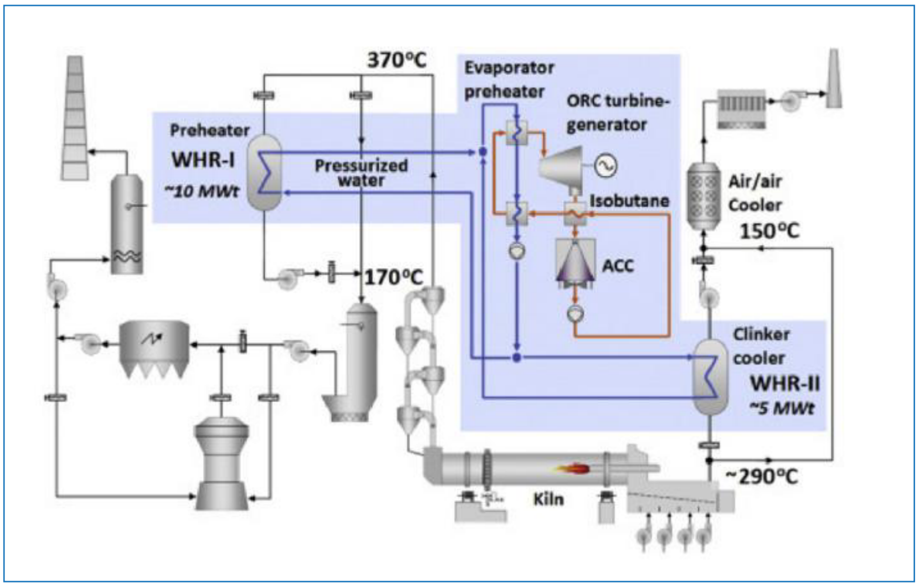

Fig. 5.18. Waste heat opportunities in cement manufacturing processes[32]
Redko, A., O. Redko, and R. DiPippo. Low-Temperature Energy Systems with Applications of Renewable Energy, Chapter 9: Industrial Waste Heat Resources; Academic Press: Cambridge, MA, USA (2020): 329-362. CCC RightsLink License N° 5471960500631
https://www.sciencedirect.com/science/article/pii/B9780128162491000091

[32] 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.

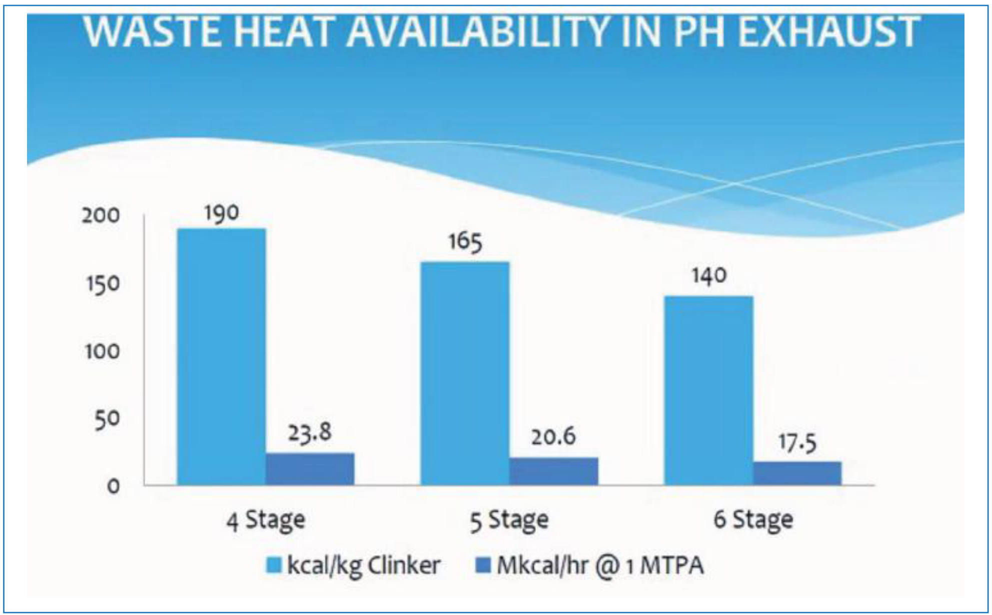

Fig. 5.19. Waste heat availability in PH exhaust[33]

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	Mkcal /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[34]

33 ICC E-Conference on Cement Industry - 4th Cementing India - 2021 https://www.indianchamber.org/icc_events/4th-cementing-india-icc-e-conference-for-the-cement-industry/

34 ICC E-Conference on Cement Industry - 4th Cementing India - 2021 https://www.indianchamber.org/icc_events/4th-cementing-india-icc-e-conference-for-the-cement-industry/

HEAT REQUIREMENT FOR CEMENT ADDITIVES Characteristics of Cement Additives (other than Limestone)				
S.No.	Material	% of addition in Cement	% moisture level	Heat requirement
1	**Gypsum**	3-5%		
a	Chemical		8-20	Met from grinding & clinker heat
b	Salt Pan			
c	Mineral		3-10	
2	**Fly ash**	15-35%		
a	Dry Fly Ash		<2%	Not needed
b	Wet Fly Ash		15-30%	Significant extra heat required
3	**Slag**	35-65%	<12%	Significant extra heat required

Fig. 5.21. Heat requirements for cement additives[35]

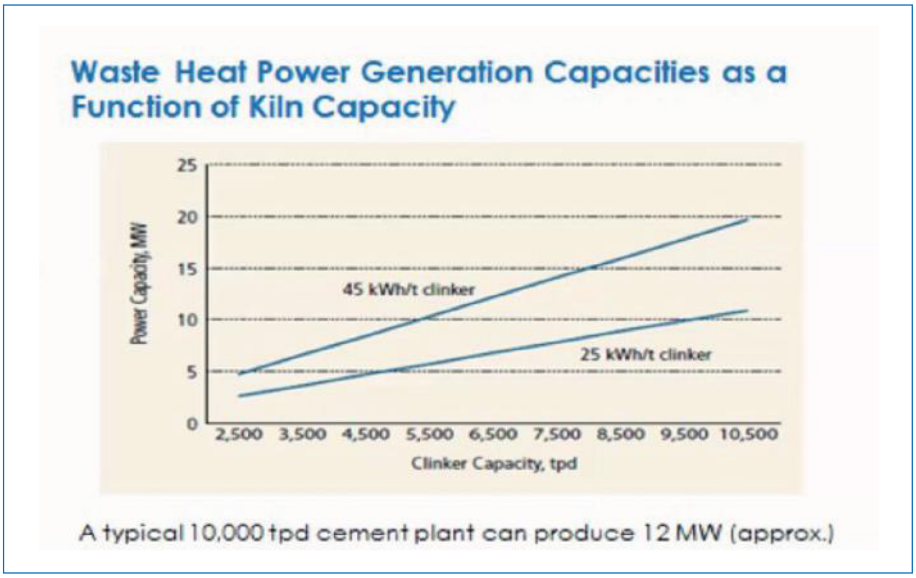

Fig. 5.22. Waste heat power generation capacities as a function of kiln capacity [36]

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.

35 ICC E-Conference on Cement Industry - 4th Cementing India - 2021 https://www.indianchamber.org/icc_events/4th-cementing-india-icc-e-conference-for-the-cement-industry/

36 ICC E-Conference on Cement Industry - 4th Cementing India - 2021 https://www.indianchamber.org/icc_events/4th-cementing-india-icc-e-conference-for-the-cement-industry/

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_{2e} per year. Airflow and fuel type were found to dominate the variation of performance.

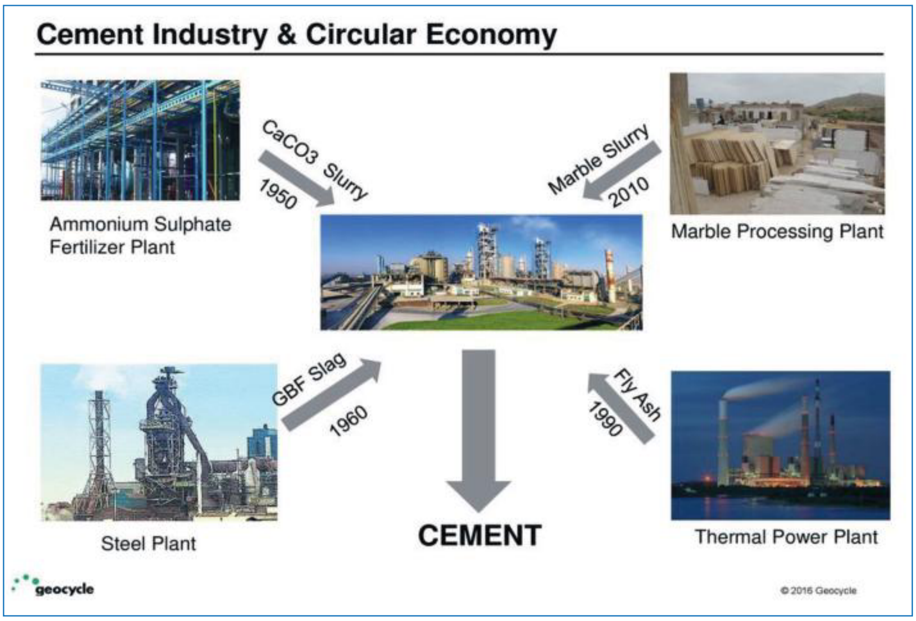

Fig. 5.23. Cement industry and circular economy
Eric Thomson, Environmentally Sound Management of Plastics Wastes through Cement Kiln Co-processing Ulhas Parlikar Dy Head, Geocycle India ACC Limited 2016-04-14. Reproduced with Permission
https://slideplayer.com/slide/14094617/

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_2 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_2 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_2 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 $Ca(OH)_2$. 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 devel-opment 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)

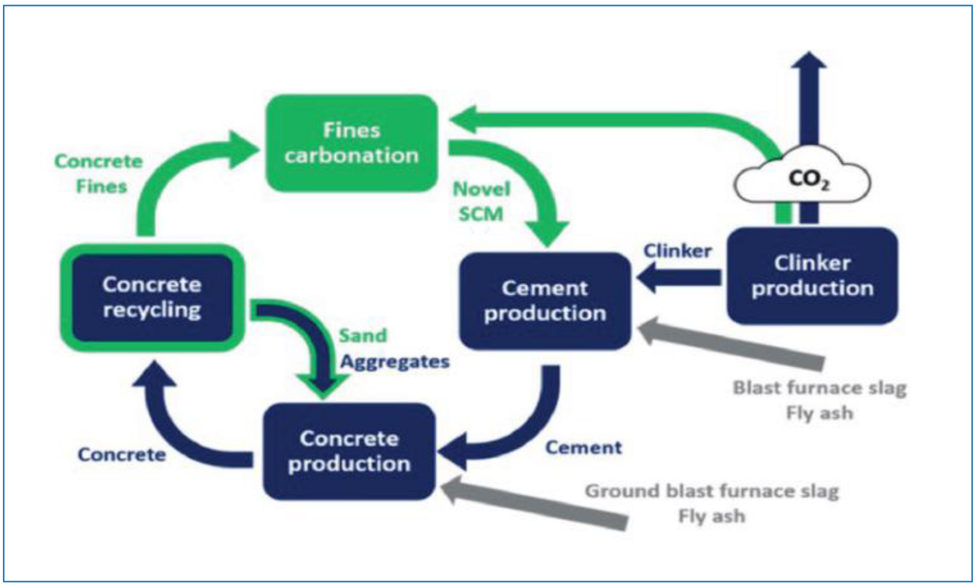

Fig. 5.24. Cement production with substantially lower CO_2 emissions[37]. Skocek, J., Zajac, M. & Ben Haha, M. Carbon Capture and Utilization by mineralization of cement pastes derived from recycled concrete. Sci Rep 10, 5614 (2020). Open Access. https://www.nature.com/articles/s41598-020-62503-z

[37] 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)

- 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_2 emissions by up to 40% and is durable against corrosion, sulphate attacks and other deterioration mechanisms, making it suitable in aggressive conditions.

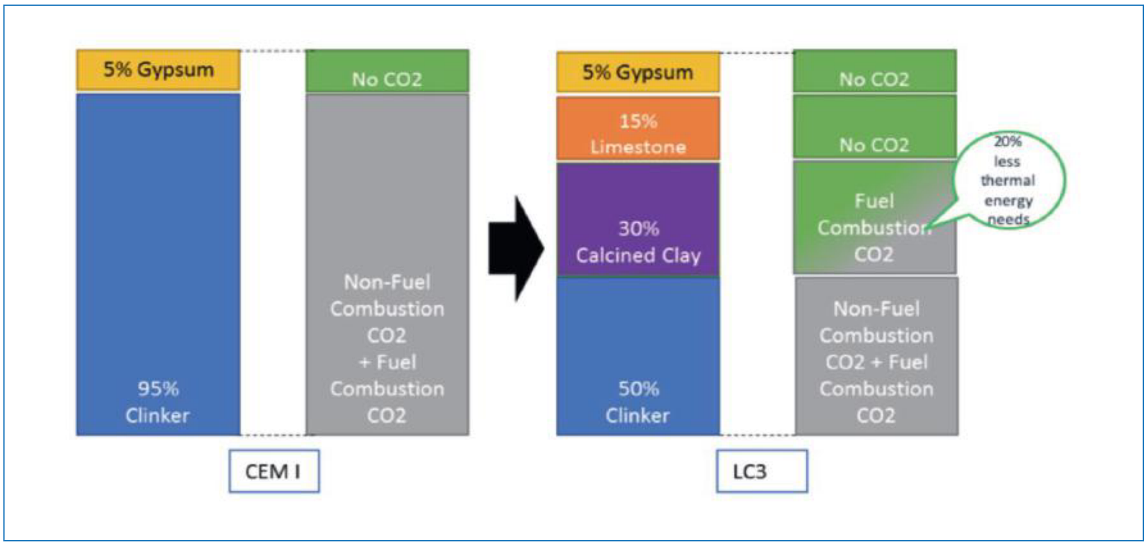

Fig. 5.25. CO_2 emission comparison - CEM 1 and LC3[38]
LC3 – Limestone Calcined Clay Cement. Reproduced with Permission
https://lc3.ch/why-lc3/

It will be economical to produce LC3 at most locations when and / or where good quality fly ash is easily available. CO_2 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.

[38] lc3.ch/why-lc3

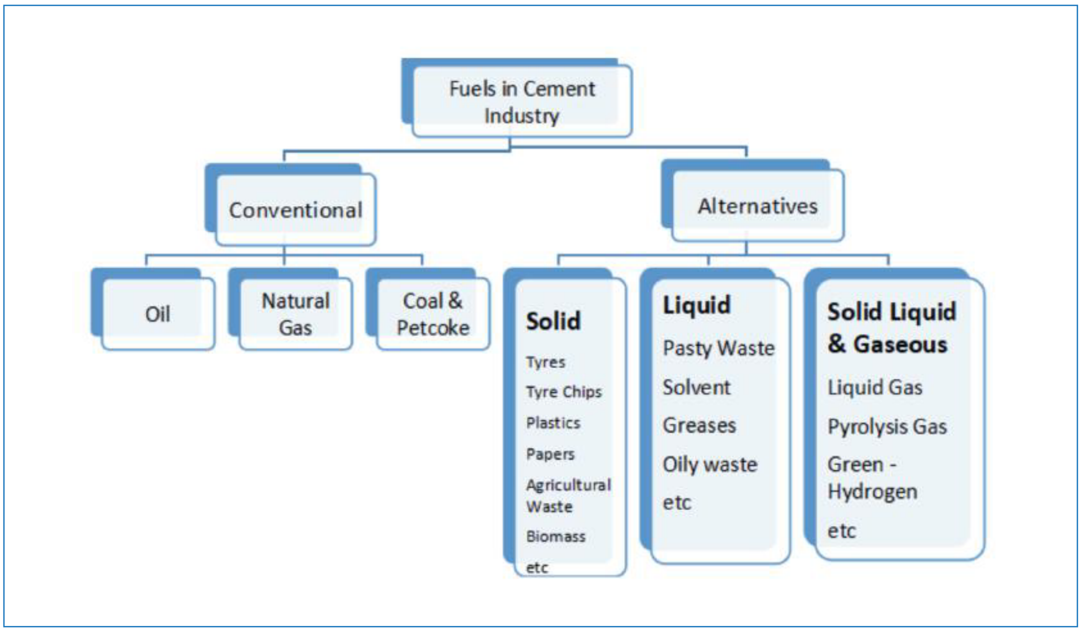

Fig. 5.26. Fuels in the cement industry[39]

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. Permission for reproduction granted by copyright owner ScienceOpen, CC BY-NC 4.0

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_2 reduction potential of 12%. The most effective way to achieve a low CO_2 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.*).

[39] https://www.scielo.br/j/jbsmse/a/y5KzJMgcDv8xvWZ9zxrbvqr/?lang=en#

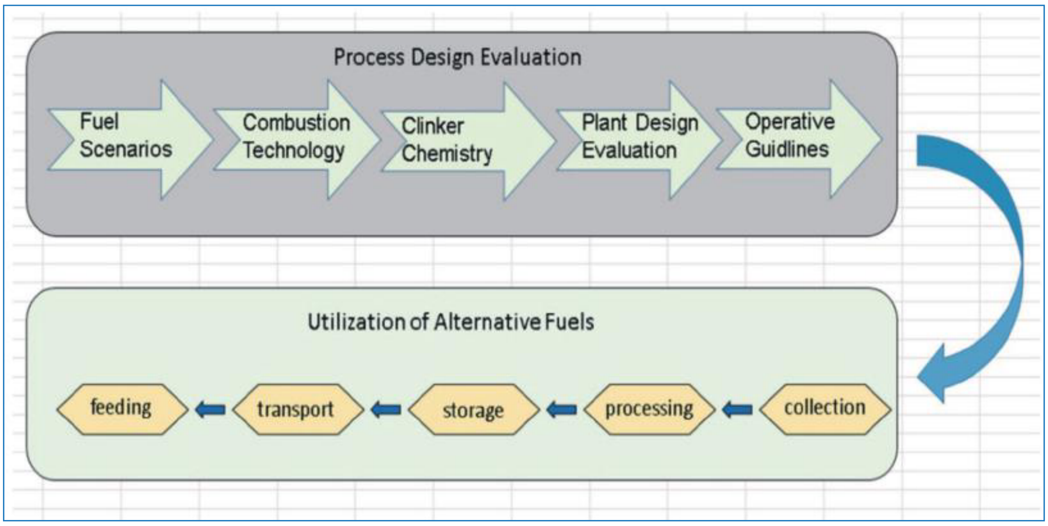

Fig. 5.27. Usage of alternative fuel[40]
Zieri, W., Ismail, I. (2019). Alternative Fuels from Waste Products in Cement Industry. In: Martínez, L., Kharissova, O., Kharisov, B. (eds) Handbook of Ecomaterials. Springer, Cham. CCC RightsLink License N° 5483150750696

- 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).

[40] https://doi.org/10.1007/978-3-319-68255-6_142

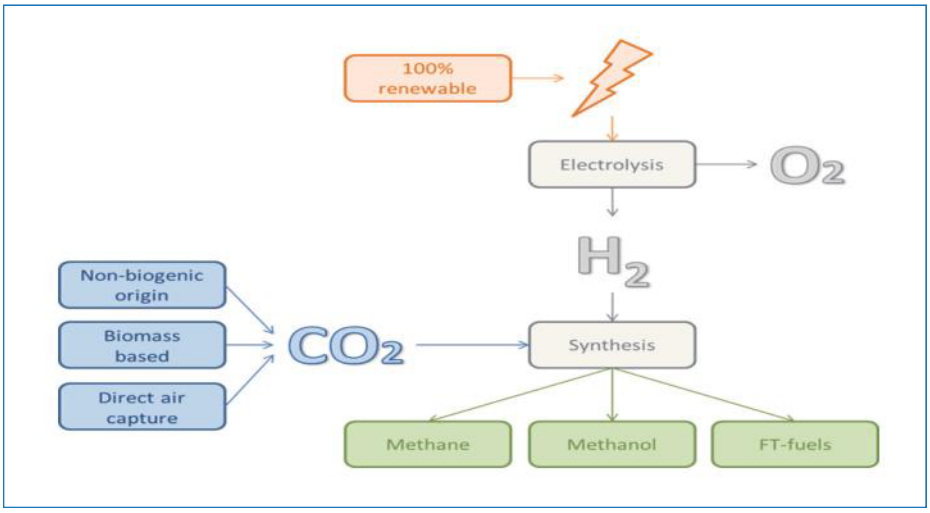

Fig. 5.28. The use of electrofuels
ETP Bioenergy -European Technology and Innovation Platform, Copyright ETIP-B
Overview on Electrofuels (etipbioenergy.eu). Reproduced with Permission
https://www.etipbioenergy.eu/overview-on-electrofuels?highlight=WyJlbGVjdHJvZnVlbHMiLCInZWxlY3Ryb2Z1ZWxzJyJd

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_2 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 ($CaCO_3$) changes the chemical reaction of limestone decomposition.

When separated, the carbon and oxygen atoms no longer pose any threat to the environment.

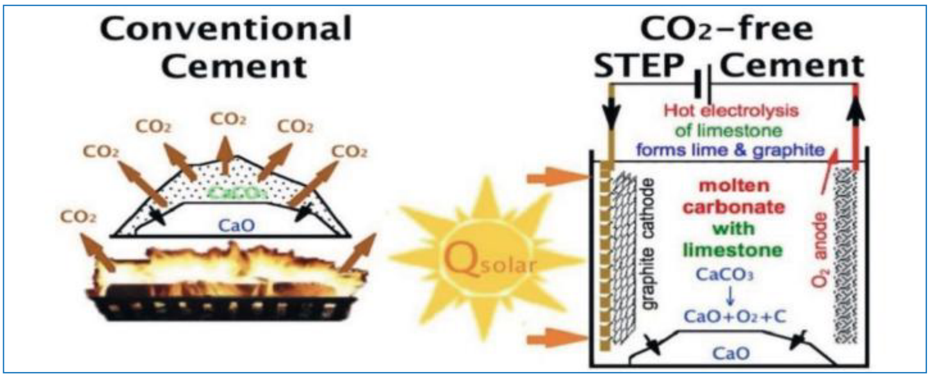

Fig. 5.29. The STEP cement process[41]
Solar thermal process produces cement with no carbon dioxide emissions . Adapted by Lisa Zyga, Phys.org
https://phys.org/news/2012-04-solar-thermal-cement-carbon-dioxide.html
from Start Licht, The Royal Society of Chemistry's journal ChemCommun 2012, 48, 6019-6021. Reproduced with Permission.

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 CO_2 emissions. The basis for producing synthetic hydrocarbon fuels is synthetic gas, or syngas, a gas mixture that contains varying amounts of CO and H_2. The CO in syngas could be produced from the sequestered CO_2 emitted during cement production, and the 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 leve as mentioned previously.

Fig. 5.30. Advantages of LC3 Technology[42]. Reproduced with Permission

[41] phys.org/news/2012-04-solar-thermal-cement-carbon-dioxide.html
[42] 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_2 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 (SiO2), aluminium oxide (Al_2O_3), calcium oxide (CaO), sodium oxide (Na_2O), 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_2 emissions intensity to 0.35 tonnes of CO_2 per tonne of cement in 2050, about 45% lower than 2010 levels, thus saving between 212 and 367 million tonnes of CO_2 ($MtCO_2$) 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_2 emissions and provide cost-benefits;
- NaOH, KOH, and Na_2SiO_3 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_2 but by the sale of value-added products that could be and would be developed with sequestered CO_2. 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_2 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 $GtCO_2$ a year in 2050, costing between USD 80 and USD 300 per tonne of CO_2.

CO_2 fuels combine hydrogen with CO_2 to produce hydrocarbon fuels, including methanol, synthetic fuels and gas. Such CO_2 fuels could utilise 1 to 4.2 $GtCO_2$ a year in 2050, yet costs rise up to USD 670 per tonne of CO_2.

In concrete building materials, CO_2 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 $GtCO_2$ in 2050 is estimated to cost between USD 30 and USD 70 per tonne of CO_2.

Bioenergy with carbon capture and storage: the operator captures CO_2 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_2.

Soil carbon sequestration: Along with the storage of 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 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.

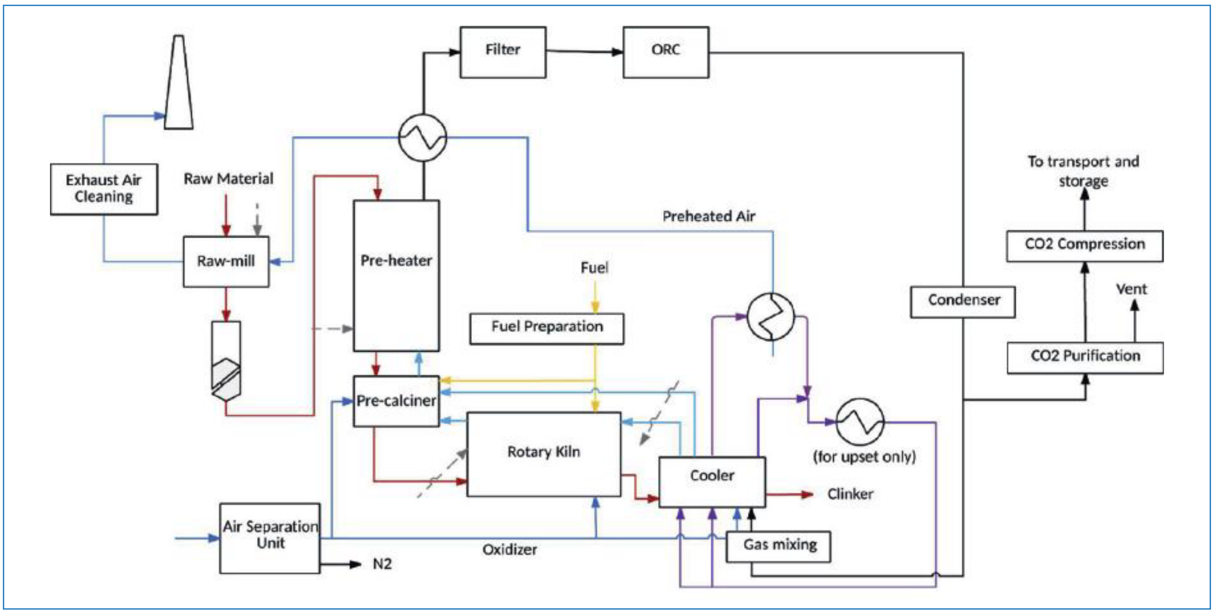

Fig. 5.31. Cement making in full oxy-fuel mode[43]
Mario Ditaranto, Jørn Bakken, Study of a full scale oxy-fuel cement rotary kiln, April 2019, International Journal of Greenhouse Gas Control 83:166-175, DOI:10.1016/j.ijggc.2019.02.008 License CC BY (Creative Commons Attribution 4.0 International)

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 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 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 CO_2 at high temperatures. In this process, CO_2 is captured through the so-called carbonation of calcium oxide (CaO) to form calcium carbonate ($CaCO_3$).

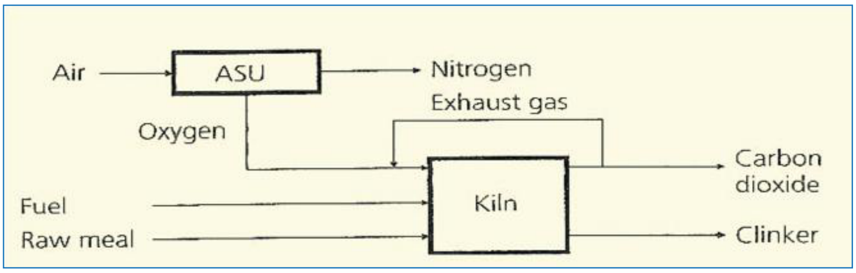

Fig. 5.32. The oxy-fuel combustion process

[43] https://www.researchgate.net/figure/Cement-making-plant-in-full-oxy-fuel-mode-showing-process-components-gas-and-clinker_fig1_332123548

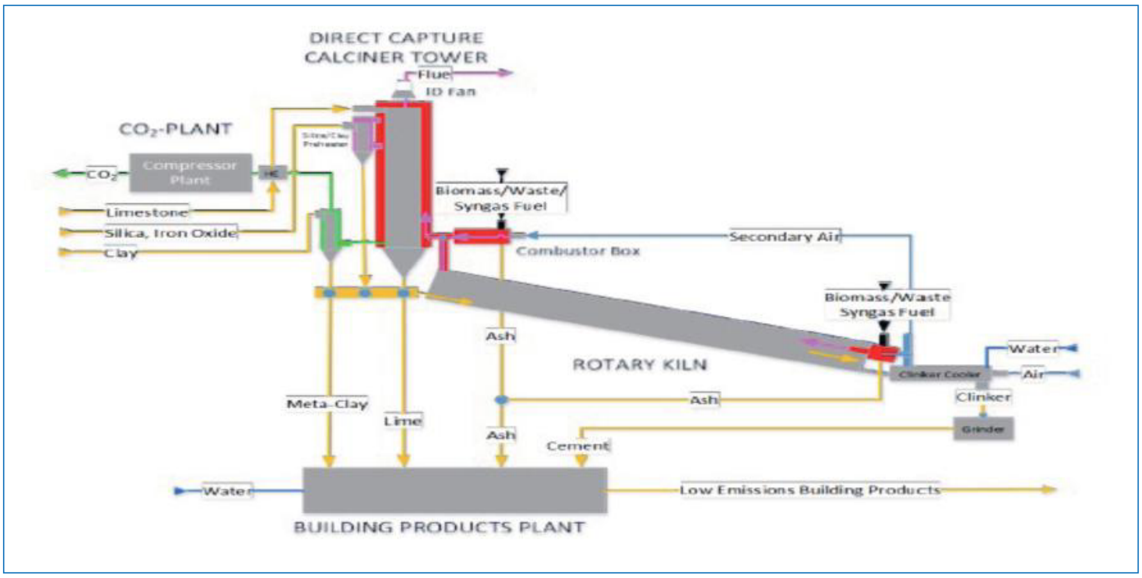

Fig. 5.33. Schematic flow sheet of the indirect calcination process with downstream option
Article "Veering Towards Carbon Capture and Transformation – An Emerging Technological Need for Carbon Dioxide Abatement Strategy" – by Dr Anjan K Chatterjee, Conmat Technologies Pvt Ltd, Kolkata, India. Reproduced with Permission. *See also* "Cement Production Technology, Principles and Practice", Anjan Kumar Chatterjee, CRC Press, Taylor and Francis Group, page 356, FIGURE 10.17:
https://nasiri.iut.ac.ir/sites/nasiri.iut.ac.ir/files//files_course/cement_production_technology_principles_and_practice.pdf

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_2 (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_2 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_2 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_2 with algae.
- The electrochemical reduction of CO_2 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_2 can and will be used in other industrial procedures. The use of CO_2 in the recarbonation of concrete and mineralisation of aggregates provides solutions for CO_2 emissions. Other uses of captured CO_2 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_2 than can be utilised;
- the economic benefits of using captured CO_2 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_2 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_2.

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_2 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_2 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_2 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_2 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.*[44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57] 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_2 footprint of cement manufacturing processes. Each column represents a combination of technologies for one project.

44 Accelerating to zero by 2040! – Architecture 2030 (https://architecture2030.org/accelerating-to-zero-by-2040/)

45 Ernest Orlando, Lawrence Berkeley National Laboratory China Energy Group, Energy Analysis Department Lynn Price, Ali Hasanbeigi, Hongyou Lu

46 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/)

47 Marta G. Plaza*, Sergio Martínez and Fernando Rubiera CO_2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations MDPI

48 CEMBUREU Position paper - Cembureau eedback to the European Commission's Public Consultation on Energy Efficiency Directive

49 Thomas Schuiz Driving sustainable productivity FL Smidth

50 Emission Reduction Approaches for the Cement Industry- AEEE.in Inside the Cement Industry: Challenges and Solutions

51 Global Cement Industry's GHG Emissions — Global Efficiency Intelligence

52 How Renewable Energy Could Support the Cement Industry's Energy Demand Kamlesh Jolapara

53 Thomas Czigler, Sebastian Reiter, Patrick Schulze, and Ken Somers Laying the foundation for zero-carbon cement McKinsey & Company

54 Low-Carbon Transition in the Cement Industry International Energy Agency

55 Use of Alternative Materials in Cement Manufacturing Cement Equipment.org

56 Hosam M. Saleh, Samir B. Eskander, Innovative cement-based materials for environmental protection and restoration sciencedirect.com/topics/engineering/blended-cement

57 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	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. 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[58].	1. Solid Waste Framework Directive (Directive 2008/98/EC) 2. Industrial Pollutant Emissions Directive (2010/75/EU) 3. Waste Shipment Regulation (1013/2006/EC)	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. 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. 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.
Japan	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.	1. Carbon recycling and materials industry growth strategy in line with carbon-neutral Green Growth Strategy for 2050 2. "Innovative Environmental Innovation Strategy"	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. 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.
Croatia	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%.	1. Green Certificates 2. Legislation for handling Construction waste material 3. EU Green Deal 4. EU Emissions Trading System (EU ETS)	1. Green Certificates are officially known as Renewable Energy Certificates (RECs). 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. 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. 4. EU ETS is the core principle of the "Carbon Trading Mechanism" under the Kyoto Protocol.

[58] 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 inannual 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.	1. Capacity restriction policies. 2. Accelerating the development of mandatory standards for the cement industry 3. CO_2 assessment 4. Organising to build “six-zero” model factories in the building materials industry	1. Includes the elimination of outdated production capacity, capacity reduction and replacement, limited peak production and strict control of new production capacity. 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. 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. 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.
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.	1. Carbon tax on fossil fuels 2. Indicator requirements for alternative fuels, raw materials, and waste recycling	1. The CO_2 tax on fuels is about USD 5 per tonne of coke. 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%.
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	1. The Swiss Energy Strategy 2050 2. Long-term climate strategy to 2050 3. Carbon tax	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). 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. 3. Since 2008 Switzerland has a CO_2 levy which has been increasing from CHF 12 /tonne in 2008 to nearly CHF 100 now.

India	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.	1. National Action Plan for Climate Change (NAPCC) 2. Coprocessing of hazardous waste 3. The Bureau of Energy Efficiency (BEE) 4. CII Energy benchmarking manual 5. BEE & UNIDO 6. Clean Development Mechanism (CDM) 7. Mission Innovation (MI)	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_2 emissions from coal-fired power plants. 2. The coprocessing of hazardous waste in the cement industries has been encouraged, with appropriate, environmentally-safe methods. 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). 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. 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. 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. 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&D funds. It also seeks to bring India's focus back to CCS/CCUS.
United States of America	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.	1. Carbon tax credits 2. Dedicated funding for carbon removal technology development 3. Industrial Sector Decarbonisation Programme	1. Carbon tax credits serve as an incentive for using decarbonisation technology, such as CCUS. 2. The first funding, in the amount of USD 60 million, was provided by House and Senate appropriators. 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.
South Africa	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.	1. Carbon tax 2. South Africa National Accreditation System (SANAS): Accreditation programme (ISO 14065) 3. South Africa National Treasury (SANT)	1. Carbon taxes have been implemented. However, the cement market in South Africa still needs more regulations for fair competition to be achieved. 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. 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.

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 recomendations 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_2 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[59].

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[60]. 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[61].

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.

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59 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)

60 Cementing the European Green Deal, the European Cement Association

61 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[62].

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 exciters 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_2 into fuel and other applications using synthetic technologies from the chemical industry.

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[62] 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_2 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_2 permanent storage[63]. 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[64].

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[65].

63 Cembureau's Building carbon neutrality in Europe, the European Cement Association
64 PCA(2021), Roadmap to carbon neutrality
65 e.g. for decarbonizing concrete

5. Pathway to net-zero CO_2 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_2/tonne clinker. According to the scenario analysis conducted by China National Building Material (CNBM), the baseline scenario is 0.8695 tonne CO_2/tonne clinker for a cement clinker emission intensity without any technical emission reduction factor; the emission reduction scenario is 0.8432 tonnes CO_2/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_2/tonne clinker. According to the CNBM scenario analysis, the cement clinker emission intensity in the baseline scenario is 0.8695 tonne CO_2/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_2/t clinker by 2060. For CEMBUREAU, the use of decarbonated raw material is expected to result in a 3.5% reduction of process CO_2 by 2030 and up to 8% by 2050[66] .

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_2 emissions from fuel. For China, the emission reduction potential of alternative fuels is 140-285 kg CO_2/t clinker. For CEMBUREAU, hundreds of kilograms of CO_2 are planned to decrease through fuel substitution[66]. 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[67].

5.1.4. Low carbon cement

The emission reduction potential for low carbon cement development is 40-70 kg CO_2/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) aluminate 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

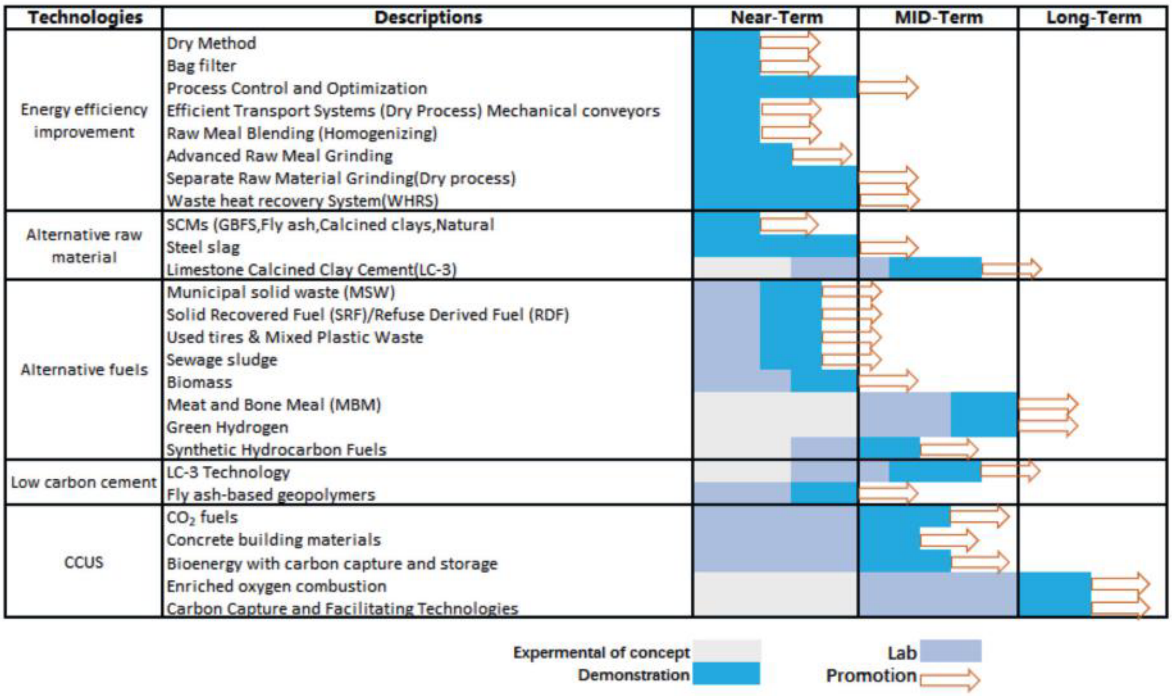
CCUS has an emission reduction potential of 200-400 kg CO_2/tonne clinker, and it might be the only technical pathway to achieving near-zero emissions in the cement industry. In view of the decisive role of CCUS technology in a carbon neutral cement industry, CCUS technology will have to be promoted on a large scale.

[66] 5C Carbon Neutral Roadmap of Cembureau, European Cement Association

[67] PCA(2021), Roadmap to Carbon Neutrality

5.2. Pathway to net-zero CO_2 emission

The pathway to net-zero CO_2 emission for the cement industry is shown in *Table 5.7*.



Technologies	Descriptions	Near-Term	MID-Term	Long-Term
Energy efficiency improvement	Dry Method			
	Bag filter			
	Process Control and Optimization			
	Efficient Transport Systems (Dry Process) Mechanical conveyors			
	Raw Meal Blending (Homogenizing)			
	Advanced Raw Meal Grinding			
	Separate Raw Material Grinding(Dry process)			
	Waste heat recovery System(WHRS)			
Alternative raw material	SCMs (GBFS,Fly ash,Calcined clays,Natural			
	Steel slag			
	Limestone Calcined Clay Cement(LC-3)			
Alternative fuels	Municipal solid waste (MSW)			
	Solid Recovered Fuel (SRF)/Refuse Derived Fuel (RDF)			
	Used tires & Mixed Plastic Waste			
	Sewage sludge			
	Biomass			
	Meat and Bone Meal (MBM)			
	Green Hydrogen			
	Synthetic Hydrocarbon Fuels			
Low carbon cement	LC-3 Technology			
	Fly ash-based geopolymers			
CCUS	CO_2 fuels			
	Concrete building materials			
	Bioenergy with carbon capture and storage			
	Enriched oxygen combustion			
	Carbon Capture and Facilitating Technologies			

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	1. Reduction of CO_2 intensity in the fuel mix 2. Low clinker factor 3. Calcined clays is used as artificial pozzolana	1. LaFargeHolcim: CCS (Svante Pressure Swing Absorption) 2. LaFarge: alternative fuel	1. CONCH: CCUS (dry ice) 2. CCUS (oil displacement or landfilling	1. NEXE: alternative fuel (100%, petroleum coke and coal to RDF, sewage, waste oil)	1. Dalmia: CCUS (CDRMax) 2. ACC: Coprocessing of plastic waste 3. JK Lakshmi: Waste heat recovery	1. Concrete: reduce the cement content and use water reducing	1. Cementa: CCS 2. Cementa & Vattenfall (CemZero): electrification/ biomass/CCS

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_2/tonne by 2040, has announced the installation of a large-scale CCUS facility with 0.5 Mt CO_2 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.

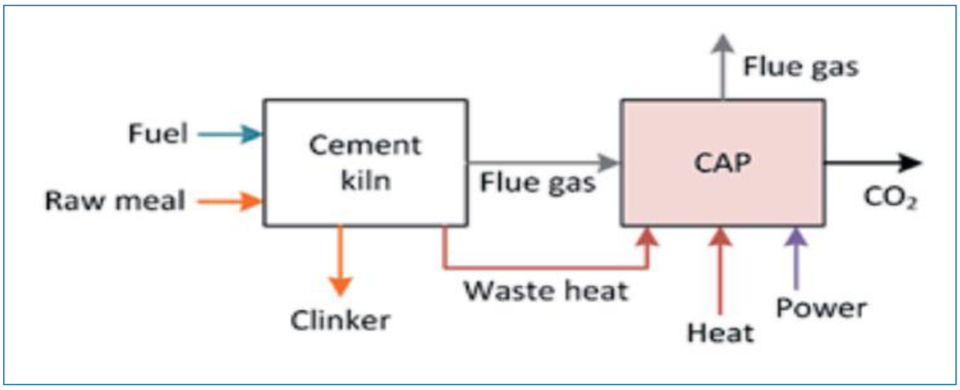


Fig. 5.34. Diagrammatic sketch of Dalmia cement
CAP: CO_2 Capture unit. Comparison of Technologies for CO_2 Capture from Cement Production—Part 2: Cost Analysis, Energies & MDPI, February 2019, Open access Creative Common CC BY license https://core.ac.uk/download/pdf/195747385.pdf

6.2. Brevik carbon capture and storage project

The Norwegian government had shortlisted Brevik for an industrial-scale CO_2 capture trial at the beginning of 2018. In September 2019, a memorandum of understanding on the capture and storage of CO_2 was signed between Heidelberg Cement and the state-owned Norwegian energy Group Equinor.

Heidelberg Cement has committed itself to reducing its specific net CO_2 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_2 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_2 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_2 capture:

- post-combustion capture
- oxyfuel
- direct separation.

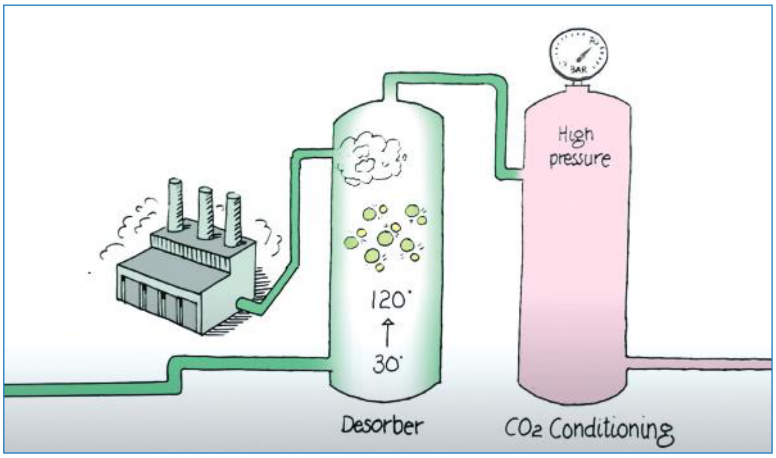


Fig. 5.35. Diagrammatic sketch of CO_2 capture

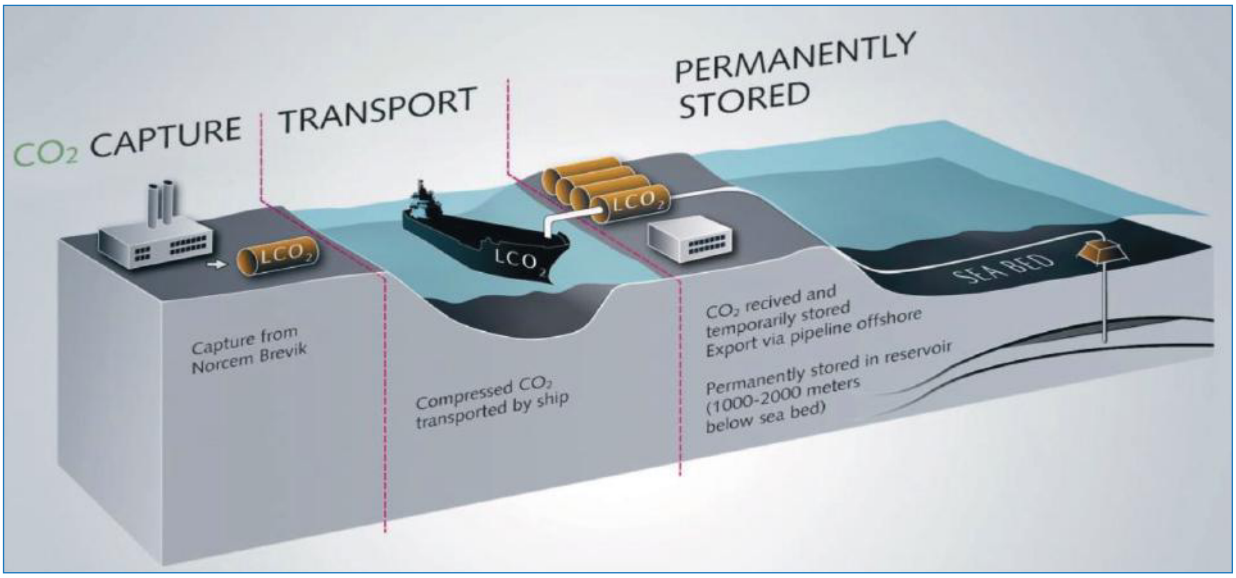


Fig. 5.36. Diagrammatic sketch of CCS in Heidelberg Cement
The Brevik CCS project. Both figure 5.35 and 5.36 from Heidelberg Materials. Reproduced with Permission.
https://www.heidelbergmaterials.com/en/carbon-capture-and-storage-ccs

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_2 emission reductions and CO_2 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_2 emissions from the cement and lime industries without significant energy or capital penalty other than compressing the CO_2.

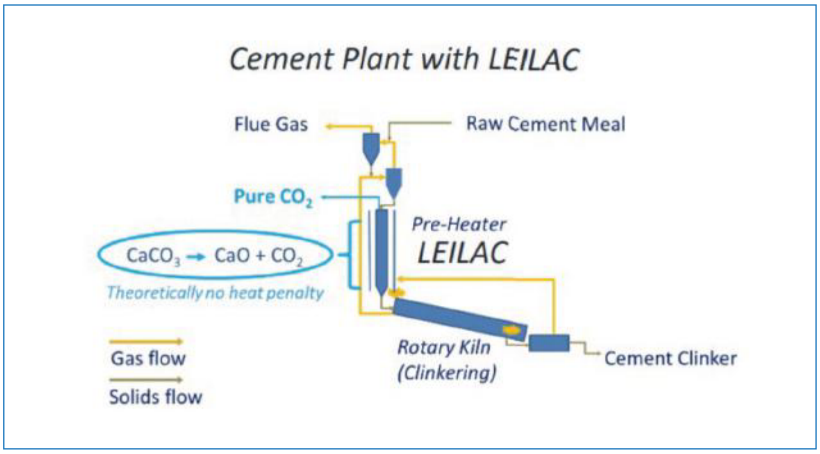


Fig. 5.37. Diagrammatic sketch of LEILAC
PowerPoint Presentation: Leilac 2 – Scaling Up Low-Carbon Solutions October 2021, Slide 4. Reproduced with Permission
https://act-anica.eu/wp-content/uploads/2021/10/Thomsen-Calix.pdf

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_2 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_2 at pilot scale. The company has called this plant the 'CO_2MENT' 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_2 emissions. The recovered CO_2 has a purity of 95% and experiments are underway to inject the captured CO_2 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_2 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_2 to building sites for injection into the concrete mix. Injection of CO_2 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_2 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_2 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_2 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[68].

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[69]

Source: Huaxin Cement: being a green industrial upgrade [J]. Environmental Economy Magazine Press, 2013(10): 40-43. Reproduced with Permission. http://qikan.cqvip.com/Qikan/Article/Detail?id=47530967&from=Qikan_Search_Index

68 White Paper on low-carbon Development of Huaxin Cement Co., LTD

69 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_2/tonne cement, thus providing a valuable contribution to the CO_2 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_2 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_2 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_2 emissions. The other is burning fuels, which roughly accounts for another 40%. 10% of the remaining CO_2 is emitted from the transport of raw materials and other processes that consume electricity. CO_2 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_2 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

AFs	Alternative Fuels
AQC	Air Quenching Cooler
CAP	CO_2 Capture unit
CCR	Calcium Carbide Residue
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CDM	Clean Development Mechanism
CEM1	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.
Cembureau	European cement association
CSI	Cement Sustainability Initiative
CST	Concentrated Solar Thermal
EE	Energy Efficiency
EU-ETS	European Union Emissions Trading System
GBFS	Ground Blast Furnace Slag
GCCA	Global Cement and Concrete Association
GHG	Greenhouse Gas
GNR	Getting the Numbers Right
IEA	International Energy Agency, based in Paris
LC3	Limestone Calcined Clay Cement
MBM	Meat and Bone Meal
MSW	Municipal Solid Waste
OPC	Ordinary Portland Cement
PH	Preheater
PLCs	Portland Limestone Cements
PVC	Polyvinyl Chloride
PPC	Portland-Pozzolana Cement
RDF	Refuse Derived Fuel
SCMs	Supplementary Cementitious Materials
SRF	Solid Recovered Fuel
tce	tons of coal equivalent
TSR	Thermal Substitution Rate
WBCSD	World Business Council for Sustainable Development
WHR	Waste Heat Recovery
WHRS	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.

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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_2 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_2- 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_2, including direct process emissions (1.4 tCO_2) 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 $GtCO_2$, representing between 7 and 9% of global anthropogenic CO_2 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_2 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_2, 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_2 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)[1]. Despite a sharp decrease in demand in 2020 due to the COVID-19 pandemic[2], 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[3]. 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.

1 World Steel in Figures 2022 - worldsteel.org

2 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).

3 World steel information in figures and graphs – see: WST01-i-84 WSIF infographic 2022 (worldsteel.org)

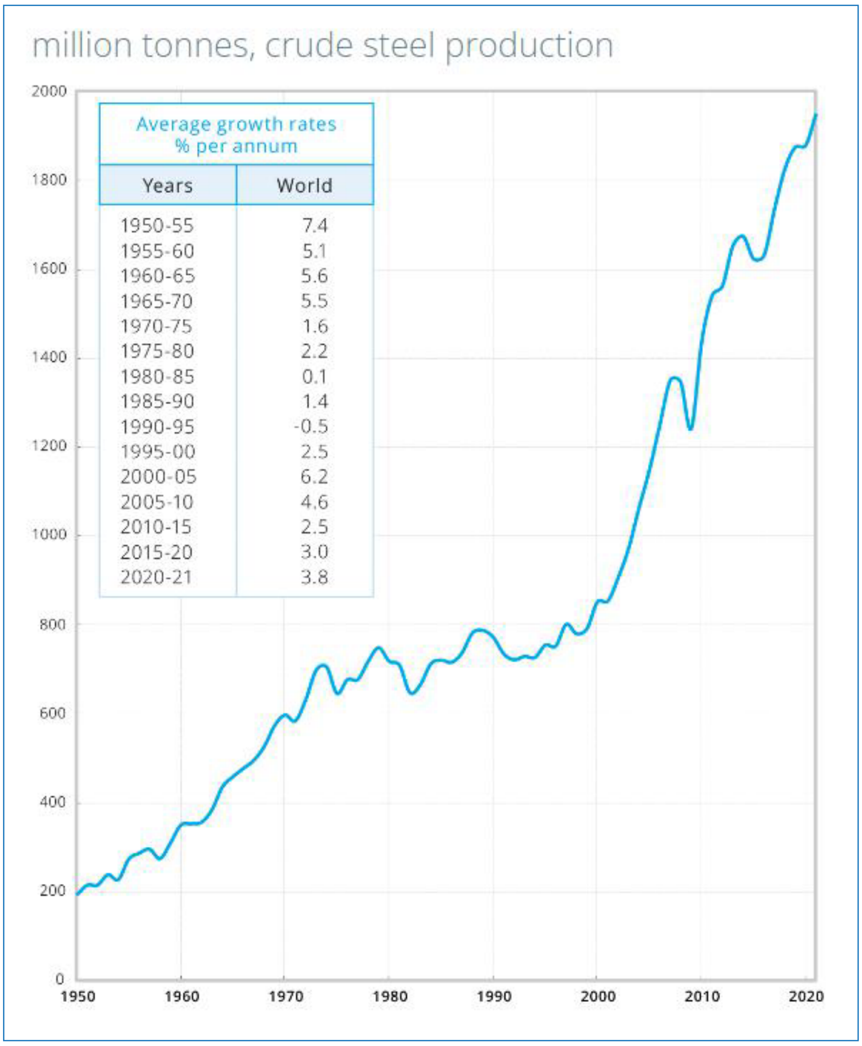

Fig. 6.2. Evolution of global steel production since 1950
World Steel Association
https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2022.pdf

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%[4]. 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.

[4] 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.

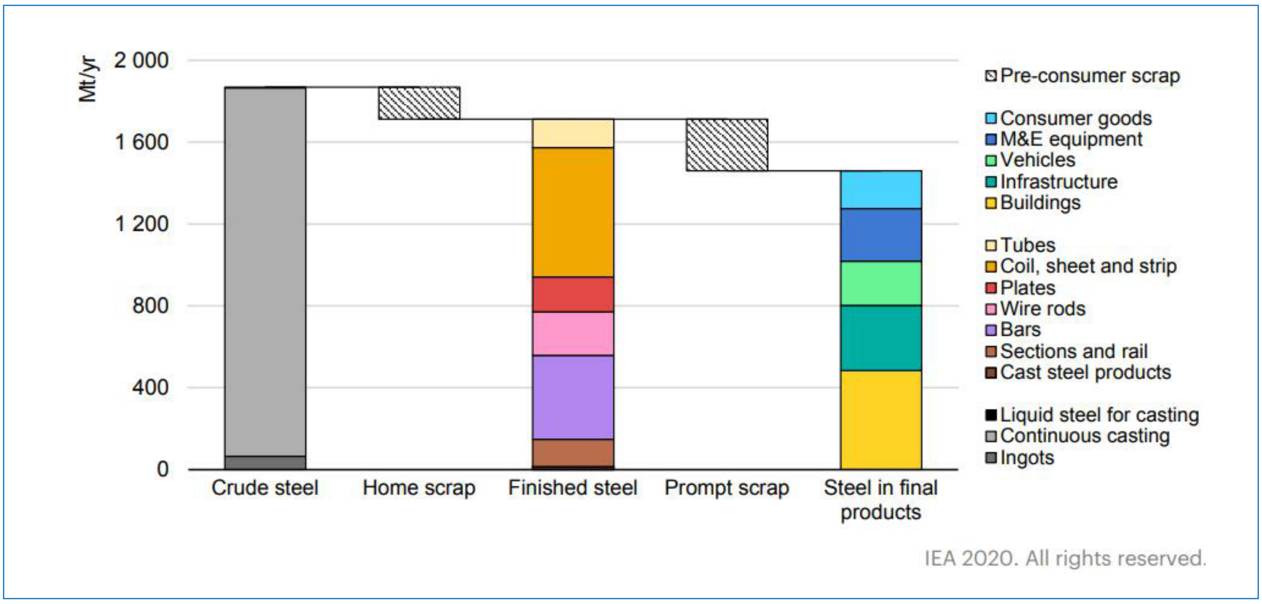

Fig. 6.3. Global steel production by product and demand segment in 2019
(For the definitions of home scrap and prompt scrap, see § 4.1)
Source: "Iron and Steel Technology Roadmap. Towards a more sustainable steelmaking". IEA (2020)[5]. Reproduced with Permission.

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.

5 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

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 [green]

Fig. 6.4. World trade in steel by area in 2020[6]

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.

6 https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2022.pdf

A breakdown of the different types of demand may be seen in the following figure[7]:

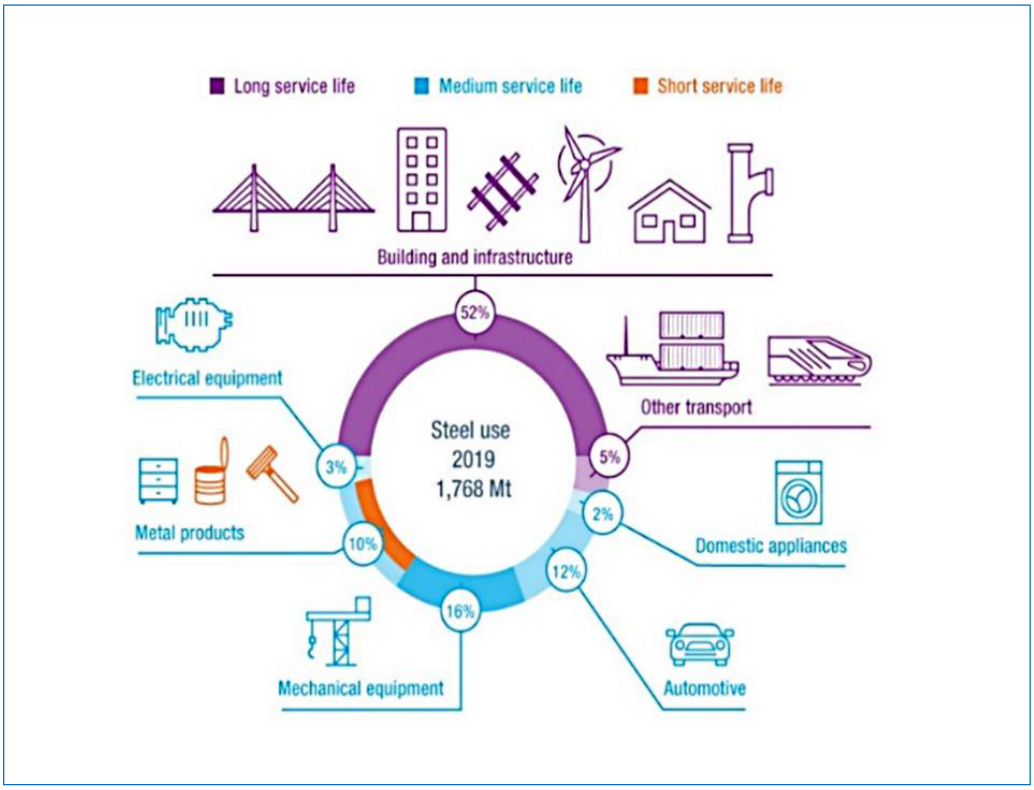

Fig. 6.5. Where steel is used.

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[8].

7 https://worldsteel.org/steel-topics/steel-markets/ Reproduced with permission.

8 See next page

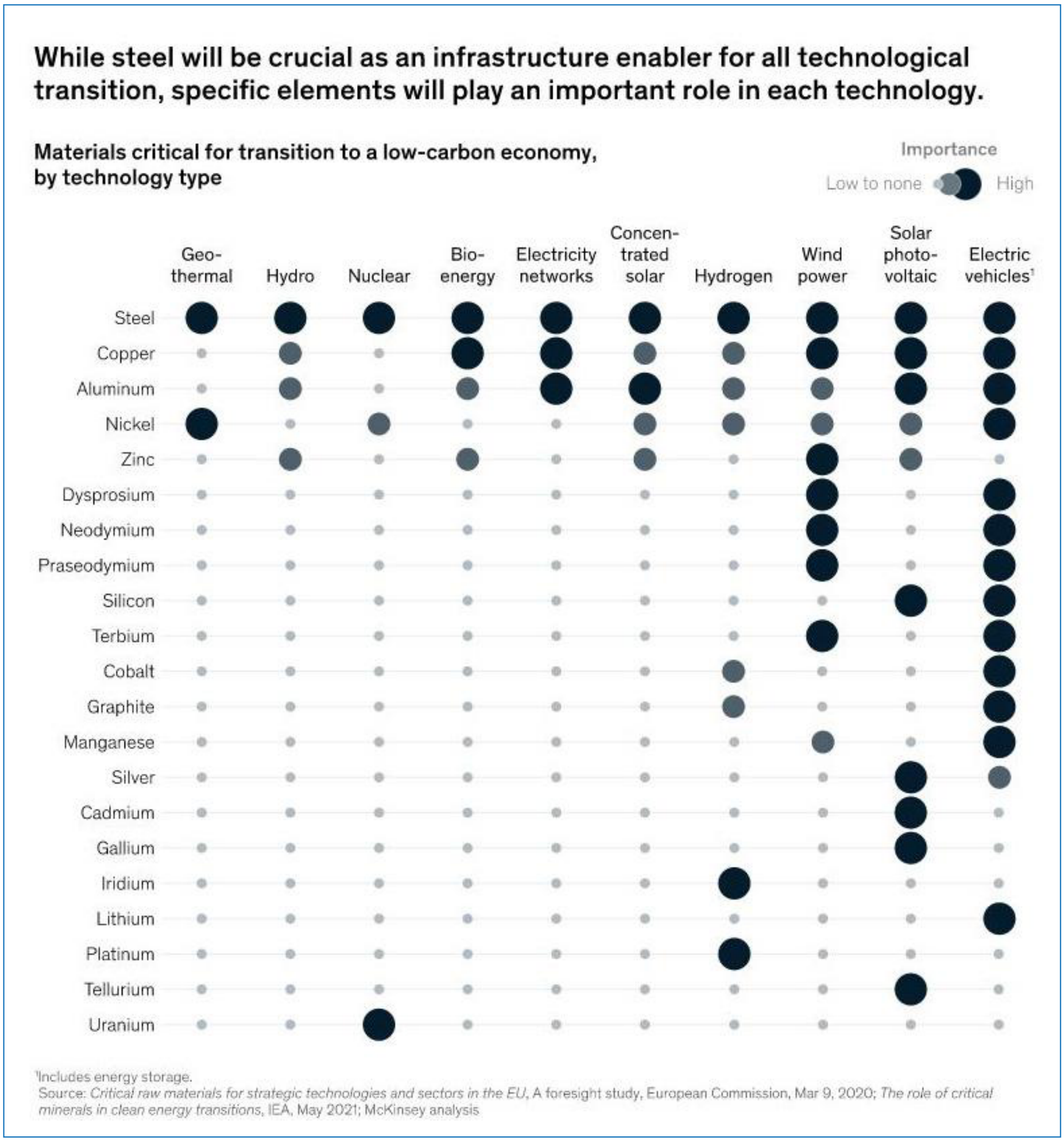

Fig. 6.6. Critical material for the infrastructural transition towards a low carbon economy across decarbonisation technologies
Exhibit from "The raw-materials challenge: How the metals and mining sector will be at the core of enabling the energy transition", January 2022, McKinsey & Company, www.mckinsey.com.
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[9].

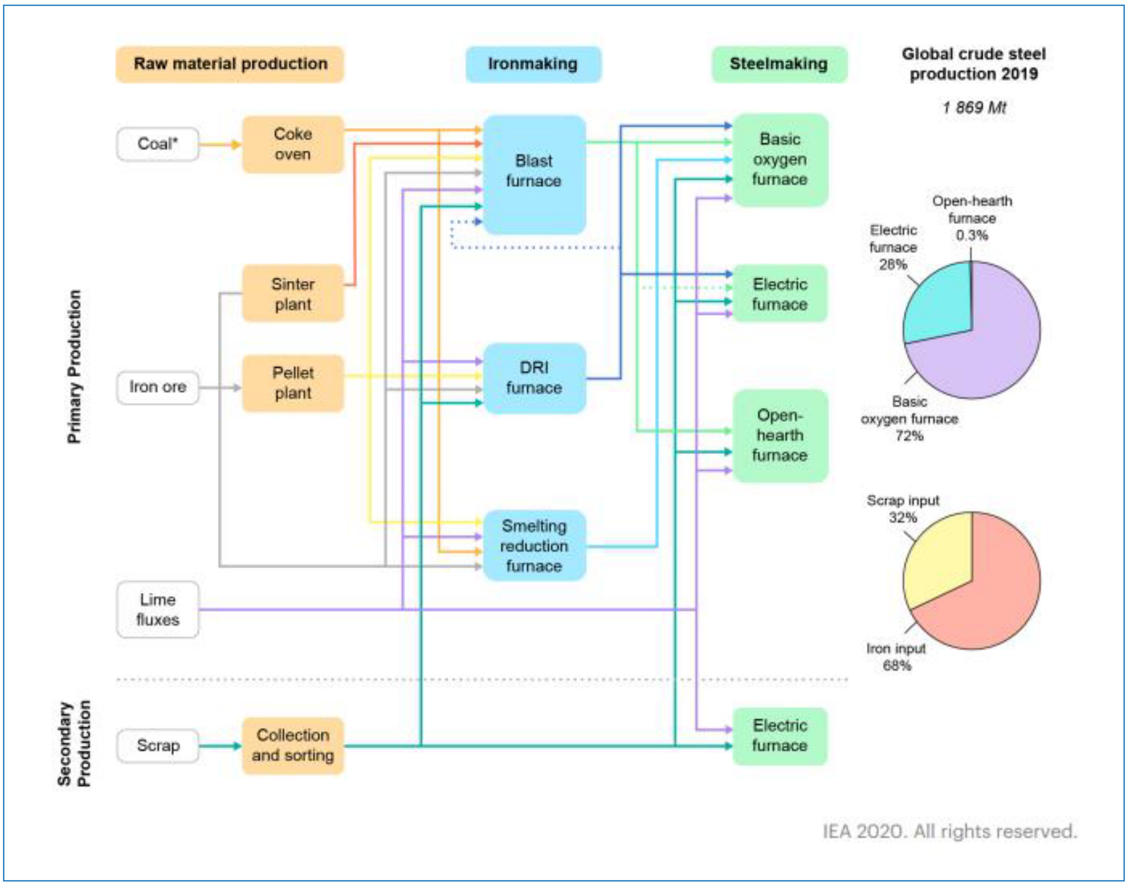

Fig. 6.7. Production processes: from raw material production to steelmaking. Reproduced with Permission

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[10].

“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”[11].

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_2 emissions, we shall refer to the three routes of:

a) BF-BOF
b) EAF
c) DRI including EAF

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9 Source: Iron and Steel Technology Roadmap - Towards more sustainable steelmaking (windows.net), Page 27

10 Recycling will be addressed specifically in a later section of this chapter.

11 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

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[12].

In terms of costs, a comparison between different routes including the scrap-based EAF, following IEA (2020), is provided below.

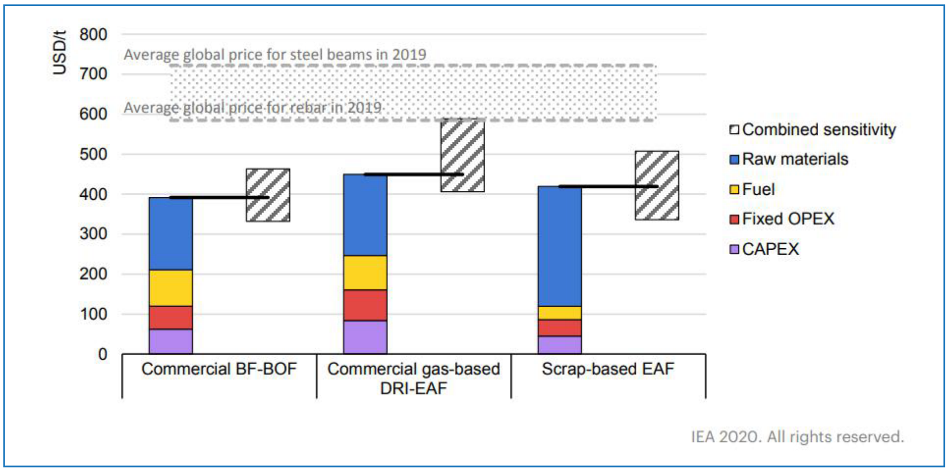

Fig. 6.8. Simplified levelized cost of steel production via major commercial routes
IEA, 2020, Iron and Steel Technology Roadmap, Towards more sustainable steelmaking, Page 31. Reproduced with Permission.
https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf

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[13] 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.

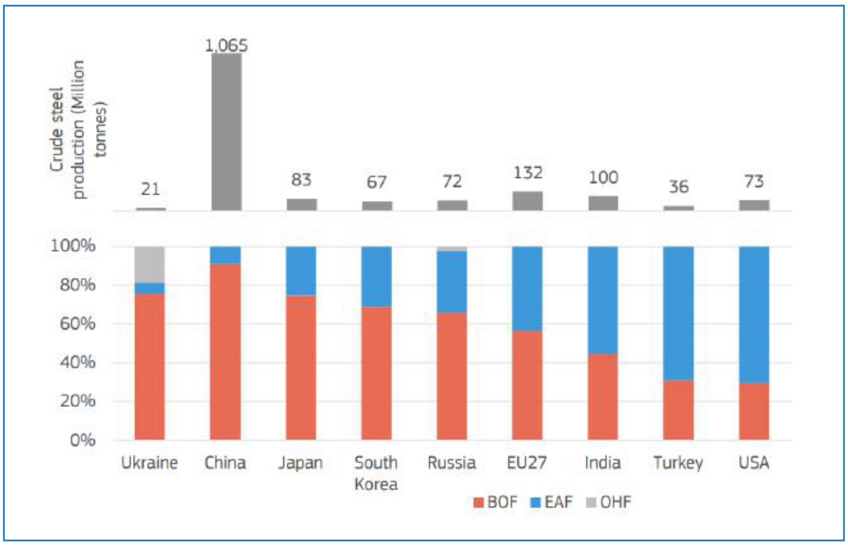

Fig. 6.9. Crude steel production by process and country, 2020 . Creative Commons Attribution (CC BY) license
Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-47147-9 (online), doi:10.2760/069150 (online), JRC127468, Page 11
https://publications.jrc.ec.europa.eu/repository/handle/JRC127468

12 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

13 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[14].

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_2- 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[15].

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"[16]. 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.

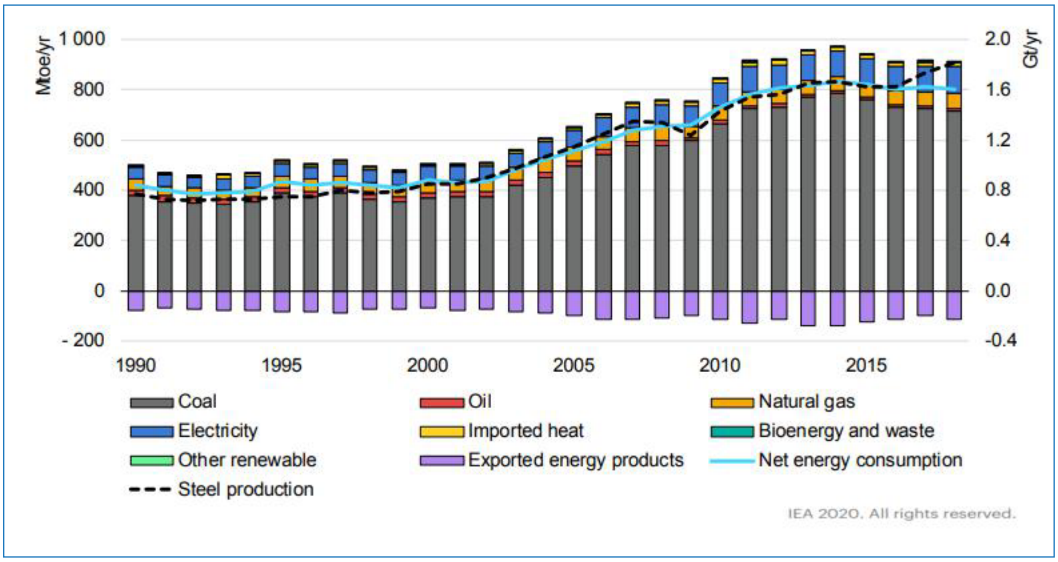

Fig. 6.10. Final Energy consumption in the steel industry
IEA, 2020, Iron and Steel Technology Roadmap, Towards more sustainable steelmaking, Page 36, Reproduced with Permission.
https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf

The energy intensities of the main production routes are the following, according to the IEA and the World Steel Association.

14 https://worldsteel.org/zh-hans/steel-by-topic/statistics/world-steel-in-figures/
15 iea.org and worldsteel.org
16 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. Reproduced with Permission
https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf

2.5. CO_2 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_2, including direct process emissions (1.4 tCO_2) and indirect emissions such as associated with external electricity; the direct emissions from the steel industry were of the order of 2.6 $GtCO_2$, representing between 7 and 9% of global anthropogenic CO_2 emissions[17].

The level of CO_2 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[18].

2.5.2. CO_2 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)[19]. "While both the primary and secondary steelmaking routes are very energy-intensive industrial processes, they can have vastly different CO_2 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_2 emissions. This processing step in the blast furnace is the most CO_2-intensive, responsible for over 50% of the total CO_2 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_2 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_2 emissions occurring at the specific steelmaking site. On average, the total BF-BOF route emits around 1.9 tCO_2/t crude steel, however there is a wide variability between countries and plants depending on the efficiency of energy and materials use".

17 iea.org and worldsteel.org
18 PowerPoint Presentation (worldsteel.org)
19 Sommers, J. (2022). "Technologies to decarbonise the EU steel industry". Joint Research Centre.

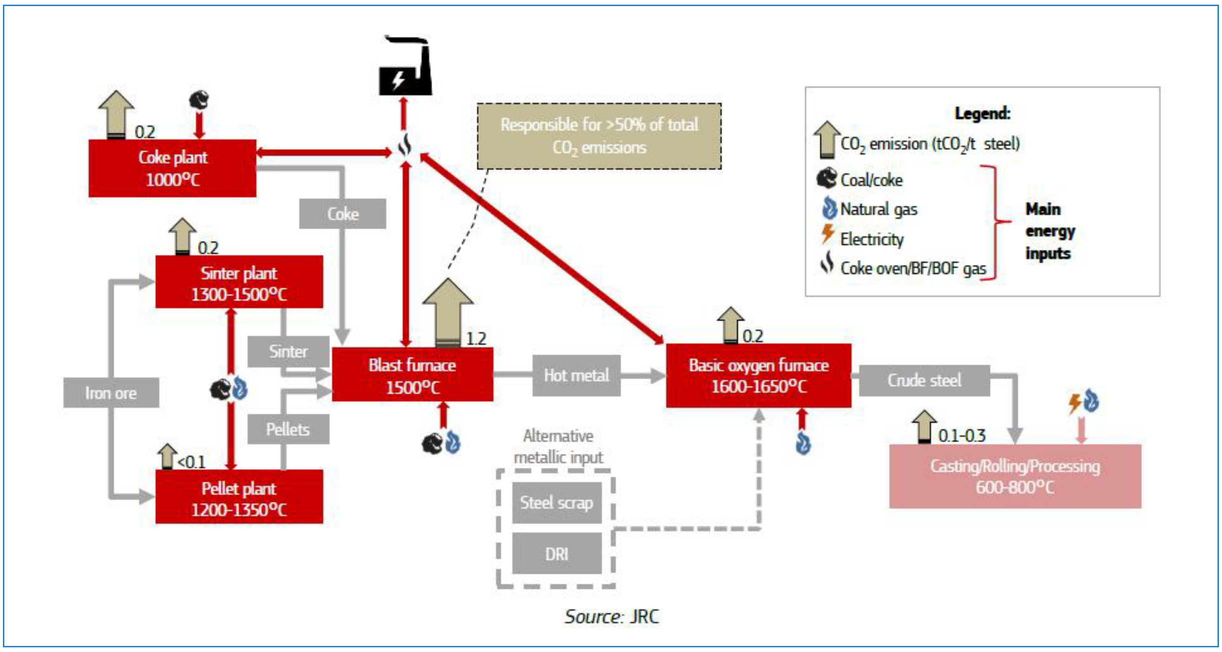

Fig. 6.12. Simplified flow diagram and CO_2 emissions of the BF-BOF route, not including the EAF
Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-47147-9 (online), doi:10.2760/069150 (online), JRC127468, Page 16, CC BY License
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_2 emissions are due to the consumption of the graphite electrodes in the EAF, which together contribute some 0.06 to 0.1 tCO_2/t steel of direct emissions (Echterhof, 2021). [*Figure 6.13. below illustrates the CO_2 emissions in the EAF process*]. A typical EAF consumes around 500 kWh of electricity per tonne of steel. At the current average CO_2 intensity of electricity in the EU, the total (direct and indirect) emissions from EAF steel melting are around 0.2-0.3 tCO_2/t steel. The indirect emissions from electricity consumption, around 0.1-0.2 tCO_2/t steel, would be avoided if the EAF used low-carbon electricity".

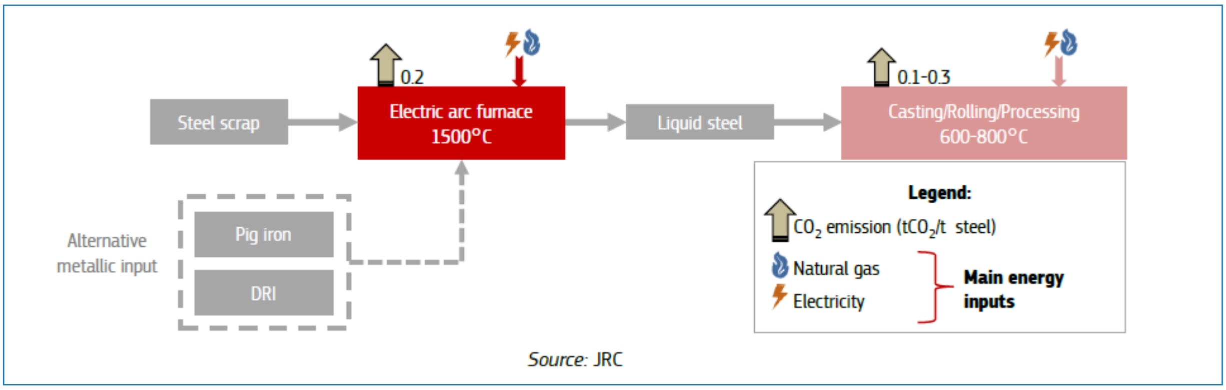

Fig. 6.13. Simplified flow diagram and CO_2 emissions of the EAF route
Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-47147-9 (online), doi:10.2760/069150 (online), JRC127468, Page 16, CC BY License
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_2. 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[20]. 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_2 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".

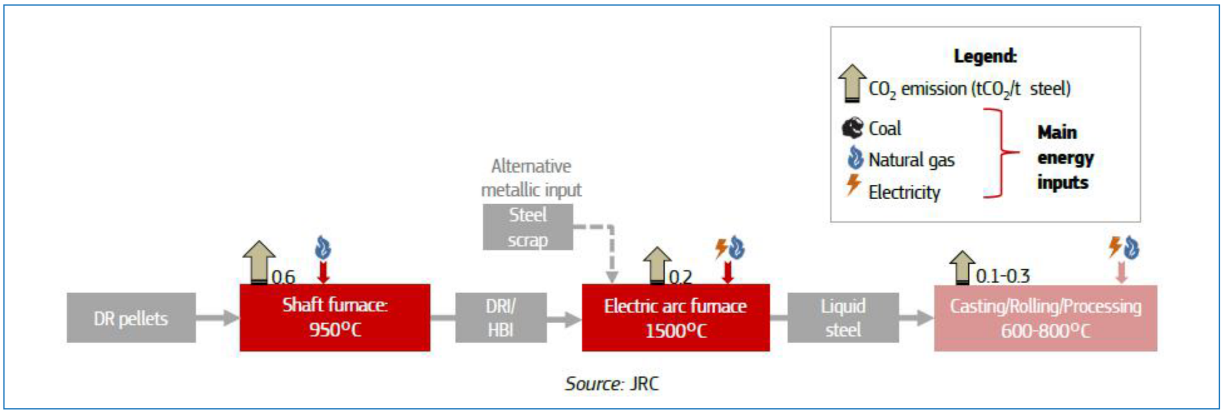

Fig. 6.14. Simplified flow diagram and CO_2 emissions of the direct reduction route, including EAF
Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-47147-9 (online), doi:10.2760/069150 (online), JRC127468, Page 17, CC BY License
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_2-intensive as natural gas, making coal-based DRI the most CO_2-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.

[20] 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).

Table 1. Specifications of current commercially available and new transformative low CO_2 production processes for steel production in greenfield production facilities.

Process	TRL Status	CO_2 Emissions, Tonne CO_2/ Tonne Steel	Capital Expenses, €/Tonne	References
Primary steel production				
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_2 capture technology [1]	TRL 6–9	CO_2 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]
Secondary steel production				
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]

[1] Capture emission points: BF, TGRBF.

Table 6.1. Commercially available low CO_2 emission production processes
Source: Toktarova et al (2020)[21]. Open License
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_2 from the top gas and reinjecting the remaining gas to the blast furnace, and biomass-derived fuels as a means to reducing CO_2 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[22] 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_2 emissions from the emerging market and developing economies, especially China. At the same time, steel production volumes would be relatively flat up to 2050.

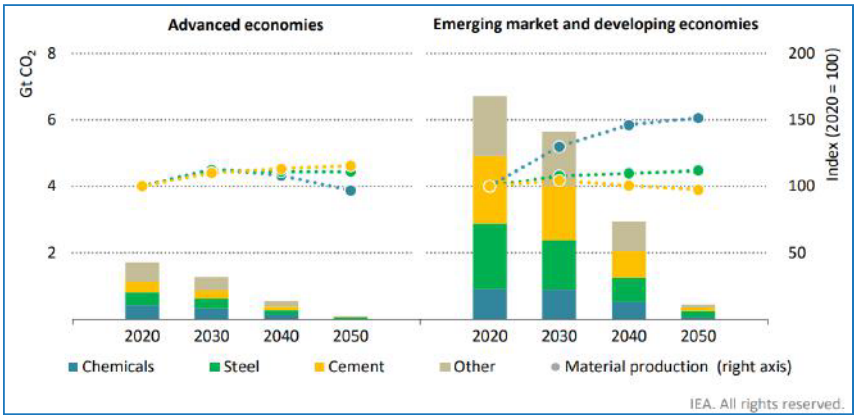

Fig. 6.15. Global CO_2 emission reduction scenarios from industry by sub-sector in the NZE
IEA Net Zero by 2050 A Roadmap for the Global Energy Sector (Figure 3.15, Page 122)
Net Zero by 2050 - A Roadmap for the Global Energy Sector (windows.net). Reproduced with Permission.

[21] 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

[22] Released May 2021 (Net Zero by 2050 – Analysis - IEA)

In the same report, figures are provided for the projection of CO_2 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_2 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[23]), CO_2 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_2 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[24].

2.5.4. Mining

Tost, M. et al. (2018)[25] estimate the global CO_2 emissions of iron ore mining in 2016 to be 38.3 Mt and 11.9 kg CO_2/t of iron ore. A similar result is provided by Skarn Associates, which estimates at 34 Mt of CO_{2e} the emissions of the scope 1 and 2 of iron ore, excluding China, and calculates 62 Mt of CO_2 were emitted for freight and downstream. (See *Fig. 6.16.*)

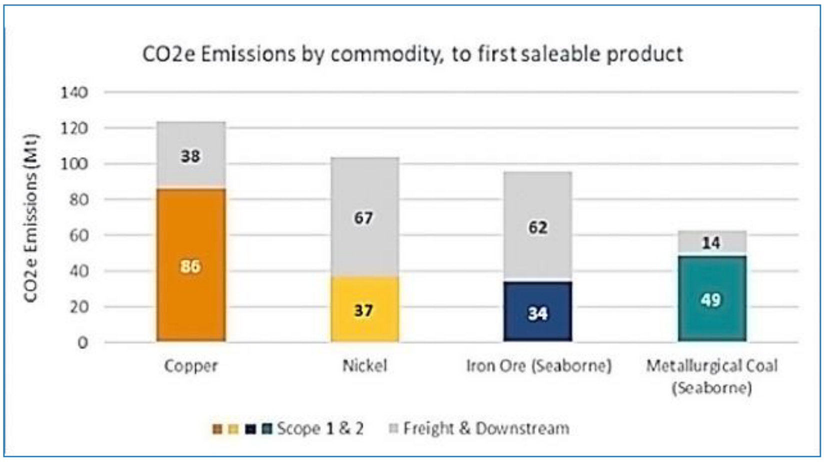

Fig. 6.16. CO_2 Emissions by commodity to first saleable product
Skarn Associates, Carbon emission curves for iron ore, copper, metal coal and nickel. Reproduced with Permission.
https://www.mining.com/carbon-emission-curves-for-iron-ore-copper-met-coal-and-nickel/

23 An energy sector roadmap to carbon neutrality in China Title of the Report (windows.net) (page 109)

24 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

25 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_2 Emissions, Water Use, and Land Requirements" Sustainability 2018,10, 2881

"The mining industry generates between 1.9 and 5.1 gigatonnes of CO_2 equivalent (CO_{2e}) 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_{2e}.

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"[26].

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.

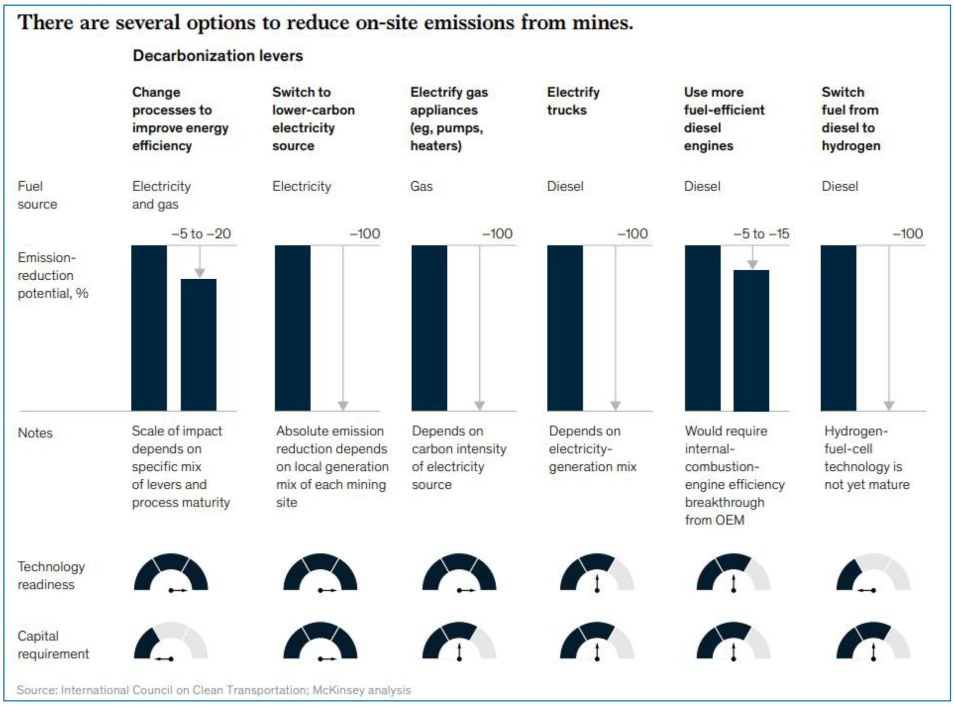

Fig. 6.17. Options for reducing on-site emissions from mining operations
Exhibit from "Climate risk and decarbonization: What every mining CEO needs to know", January 2020, McKinsey & Company, www.mckinsey.com.
Climate risk and decarbonization: What every mining CEO needs to know | McKinsey

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[27].

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

[26] "Climate risk and decarbonization: What every mining CEO needs to Know" (2020) McKinsey

[27] 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_2) 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.

a) 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.

b) Diesel fuel[28] used in vehicles (haul trucks, excavators, drills, loaders, dozers) and machinery, including power gensets and other applications.

Kumar Katta, A. et al. (2019)[29] 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.

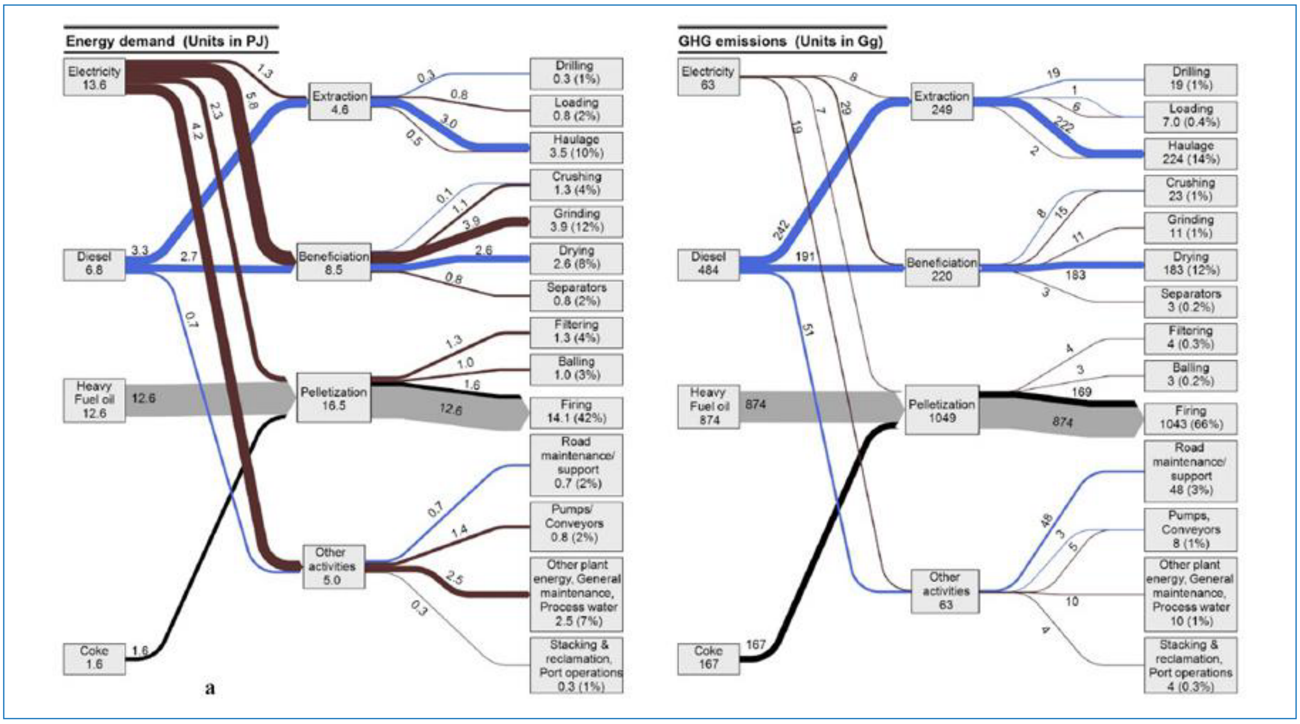

Fig. 6.18. Sankey diagram: Canada's iron mining energy demand (left) and GHG emission (right) in 2016.
Source: Anil Kumar Katta, Mattew Davis, Amit Kumar, Department of Mechanical Engineering University of Alberta: Development of disaggregated energy use and greenhouse gas emission footprints in Canada's iron, gold, and potash mining sectors, Page 10, in Resources, Conservation and Recycling, Volume 152, January 2020, CCC RightsLink License N° 5471400890674
https://www.sciencedirect.com/science/article/abs/pii/S092134491930391X?via%3Dihub

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

[28] 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.

[29] 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

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 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_2 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[30].

	Strategy	Examples	Current Outlook
BF / BOF Efficiency Programmes	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
Biomass Reductants	Use biomass as alternative fuel source	Tecnored process	Available in localised regions where biomass is available – South America & Russia
Carbon Capture & Usage	Capture CO_2 emissions and create new products	Bioethanol production from CO_2 emissions	Yet to be proven at industrial scale within steel industry. Some examples within Cement.
Electric Arc	Maximise recycling via EAF	EAF used to melt scrap	Technology available at scale
DRI & Electric Arc manufactured by NG	Replace some scrap with DRI	DRI plants already utilise NG	Technology available at scale
DRI manufactured by Hydrogen in EAF	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_2 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_2 of new primary steel. Maximising the share of recycled steel is an important lever to reduce CO_2 emissions.

30 Exhibit from "Decarbonization challenge for steel", June 2020, McKinsey & Company, 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

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[31]." 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[32].

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_2 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[33], and - the automation and electrification of transport[34].

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.

31 JRC Publications Repository - Technologies to decarbonise the EU steel industry (europa.eu)

32 Reuters News 2022-02-07 UPDATE 1-China plans to increase iron ore output, boost use of steel scrap | Reuters

33 https://www.boliden.com/sustainability/case-studies/climate-smart

34 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[35].

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[36]."

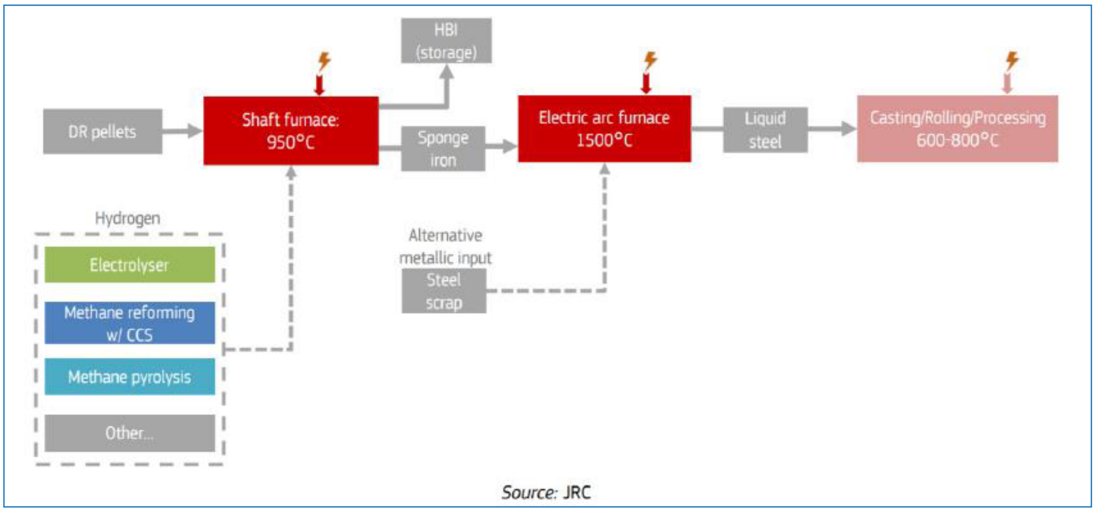

Fig. 6.19. Simplified flow diagram of the hydrogen DRI process
Somers, J., Technologies to decarbonise the EU steel industry, EUR 30982 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-47147-9 (online), doi:10.2760/069150 (online), JRC127468, Page 24. CC BY License

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

35 https://www.ovako.com/en/newsevents/stories/first-in-the-world-to-heat-steel-using-hydrogen/
36 https://publications.jrc.ec.europa.eu/repository/handle/JRC127468

CO_2 emissions average around 1.85 tonnes of carbon dioxide per tonne of steel produced (World 2020, Steel Association[37]). 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_2 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[38].

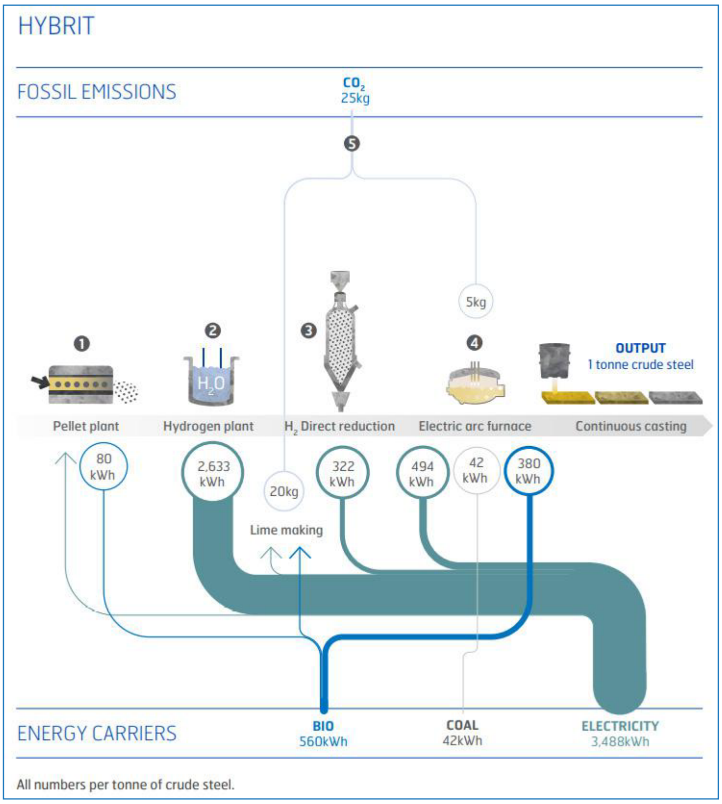

Fig. 6.20. CO_2 emissions using HYBRIT technology. Reproduced with Permission

- 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.

37 https://worldsteel.org/publications/policy-papers/climate-change-policy-paper/

38 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 pyrolised. 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_2 emissions, substantial energy savings were found [39].

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[40].

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_2 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[41].

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[39] 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

[40] Ref: Unique plant for renewable energy gas and bio-coke | Höganäs (hoganas.com)

[41] JRC Publications Repository - Technologies to decarbonise the EU steel industry (europa.eu), pp. 36-37 https://publications.jrc.ec.europa.eu/repository/handle/JRC127468

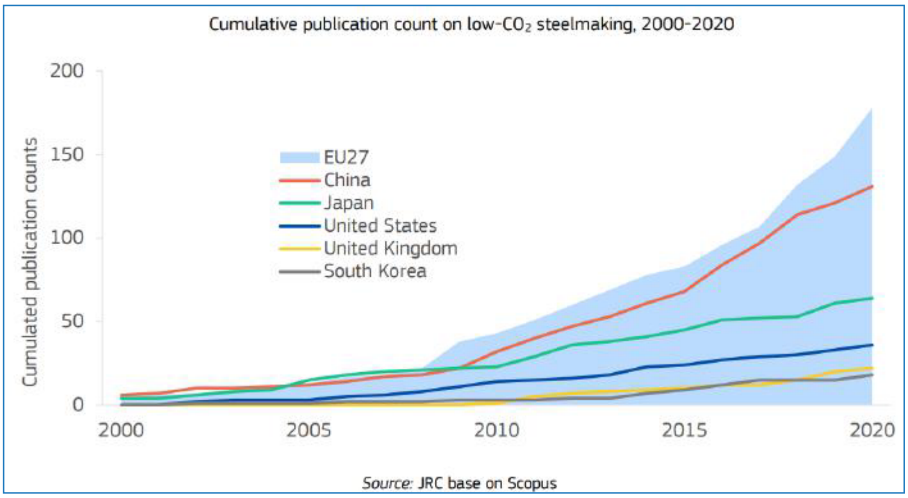


Fig. 6.21. Cumulative publication count on low-CO_2 steelmaking, 2000-2020

In Korea, the COOLSTAR project (CO_2 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_2 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_2 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_2 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). Reproduced with Permission 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 $\prec$ 0.06~0.1% and Sn $\prec$ 0.01~0.02%. For crude steel production in the electric furnace process, more typical ranges are Cu $\prec$ 0.18~0.3% and Sn $\prec$ 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_2 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.*.

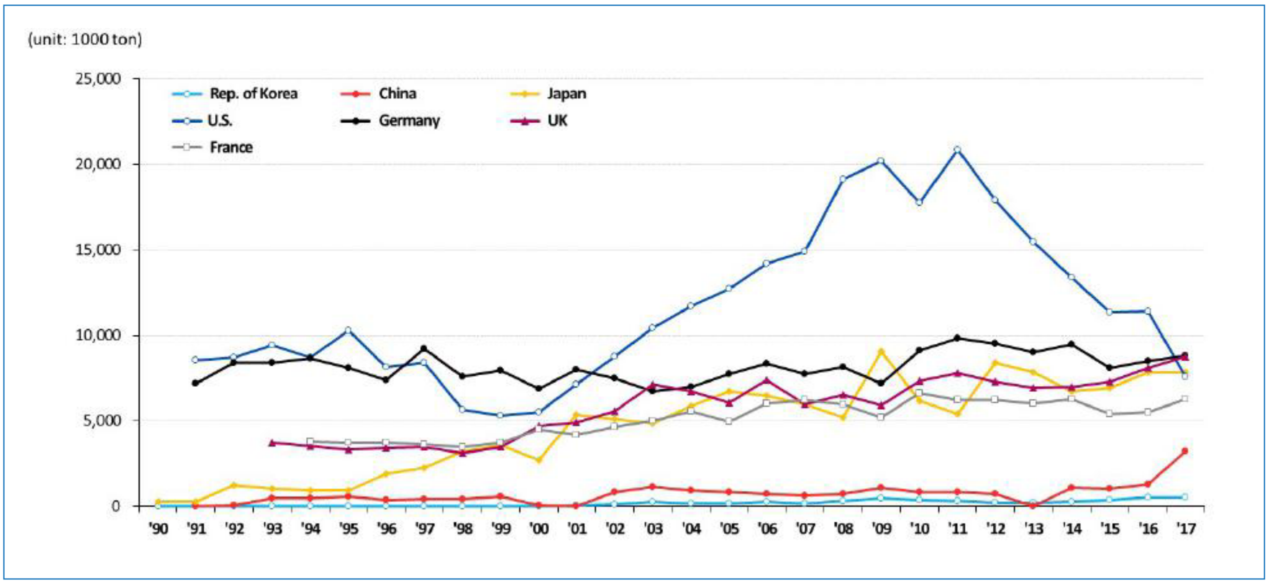


Fig. 6.22a. Scrap export amounts by the major export countries, plus China and Korea.
Provided by Il Sohn, member of the group of authors for this chapter.

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.

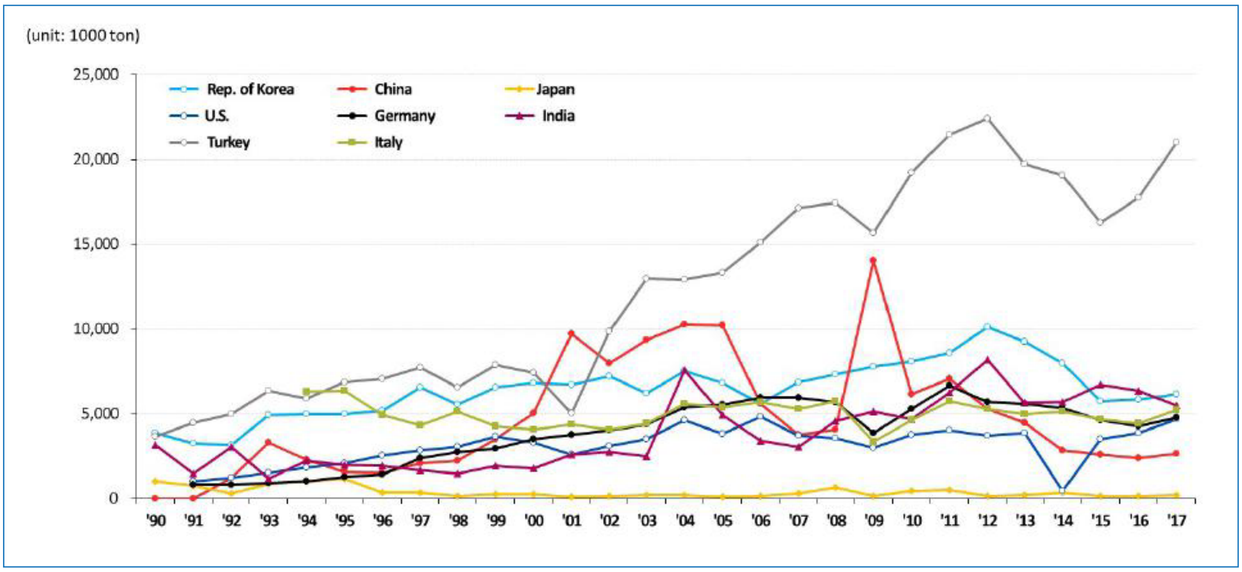


Fig. 6.22b. Scrap import amounts by the major import countries.
Provided by Il Sohn, member of the group of authors for this chapter.

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.

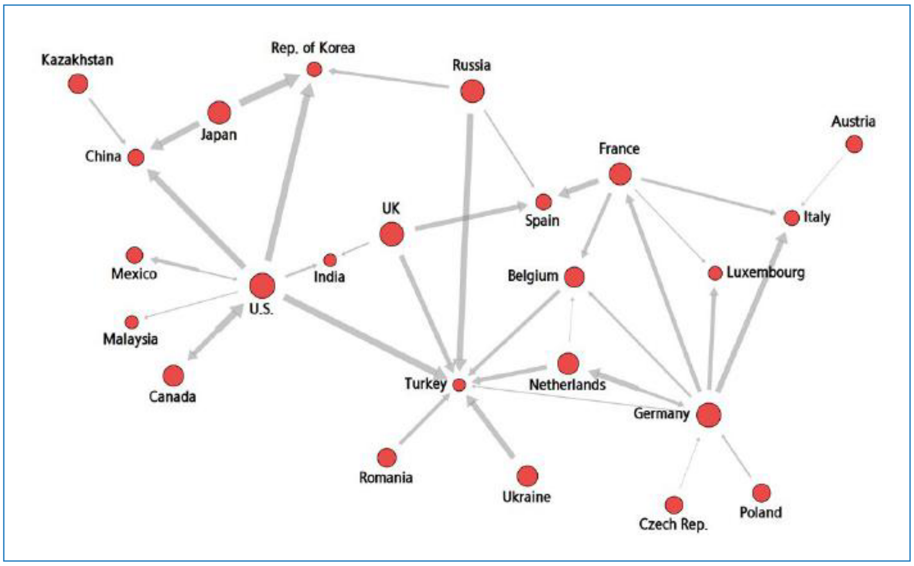


Fig. 6.23. Export network analysis of ferrous scrap from 1990 to 2017. Thicker lines correspond to larger export volumes.
Figure provided by Il Sohn, member of the group of authors for this chapter.

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 (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 Metallics Association (IIMA)[42], 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
Basic grade	3.5 - 4.5	≤1.25	≤1.0	≤0.05	0.08-0.15
Foundry	3.5 - 4.1	2.5 - 3.5	0.5 - 1.2	≤0.04	≤0.12
High Purity/Nodular	3.7 - 4.7	0.05 -1.5	≤0.05	≤0.025	≤0.035

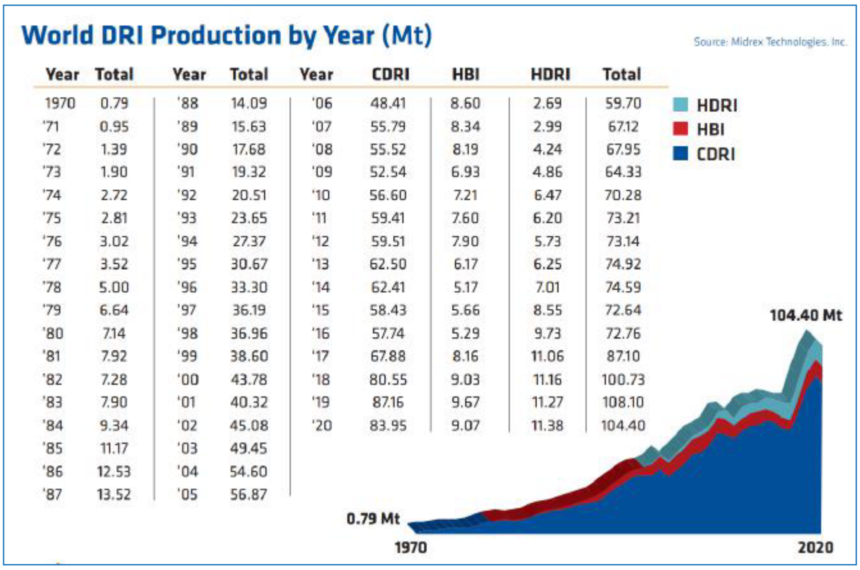
Table 6.6. Typical pig iron chemical composition by the three major pig iron types according to the IIMA.

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.*.

[42] https://www.metallics.org/pig-iron.html



Year	Total	Year	Total	Year	CDRI	HBI	HDRI	Total
1970	0.79	'88	14.09	'06	48.41	8.60	2.69	59.70
'71	0.95	'89	15.63	'07	55.79	8.34	2.99	67.12
'72	1.39	'90	17.68	'08	55.52	8.19	4.24	67.95
'73	1.90	'91	19.32	'09	52.54	6.93	4.86	64.33
'74	2.72	'92	20.51	'10	56.60	7.21	6.47	70.28
'75	2.81	'93	23.65	'11	59.41	7.60	6.20	73.21
'76	3.02	'94	27.37	'12	59.51	7.90	5.73	73.14
'77	3.52	'95	30.67	'13	62.50	6.17	6.25	74.92
'78	5.00	'96	33.30	'14	62.41	5.17	7.01	74.59
'79	6.64	'97	36.19	'15	58.43	5.66	8.55	72.64
'80	7.14	'98	36.96	'16	57.74	5.29	9.73	72.76
'81	7.92	'99	38.60	'17	67.88	8.16	11.06	87.10
'82	7.28	'00	43.78	'18	80.55	9.03	11.16	100.73
'83	7.90	'01	40.32	'19	87.16	9.67	11.27	108.10
'84	9.34	'02	45.08	'20	83.95	9.07	11.38	104.40
'85	11.17	'03	49.45					
'86	12.53	'04	54.60					
'87	13.52	'05	56.87					

Fig. 6.24. World DRI annual production from 1970 to 2020 according to Midrex Technologies, Inc. Reproduced with Permission (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. Steelmakers 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_2) 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[43]". 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_2 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

43 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_2 emission taxes increasing towards EUR 100/tCO_2, 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 electrolysers, transport, storage networks all being required.

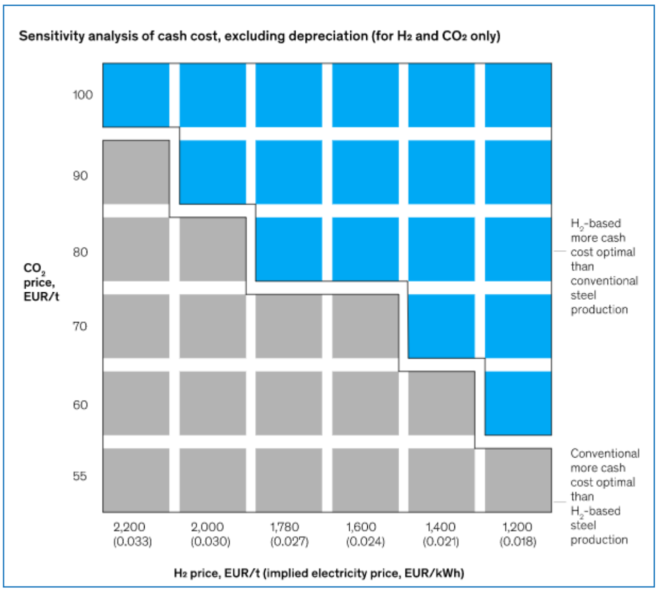


Fig. 6.25. Hydrogen Price vs. CO_2 price[44].

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.

[44] 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.

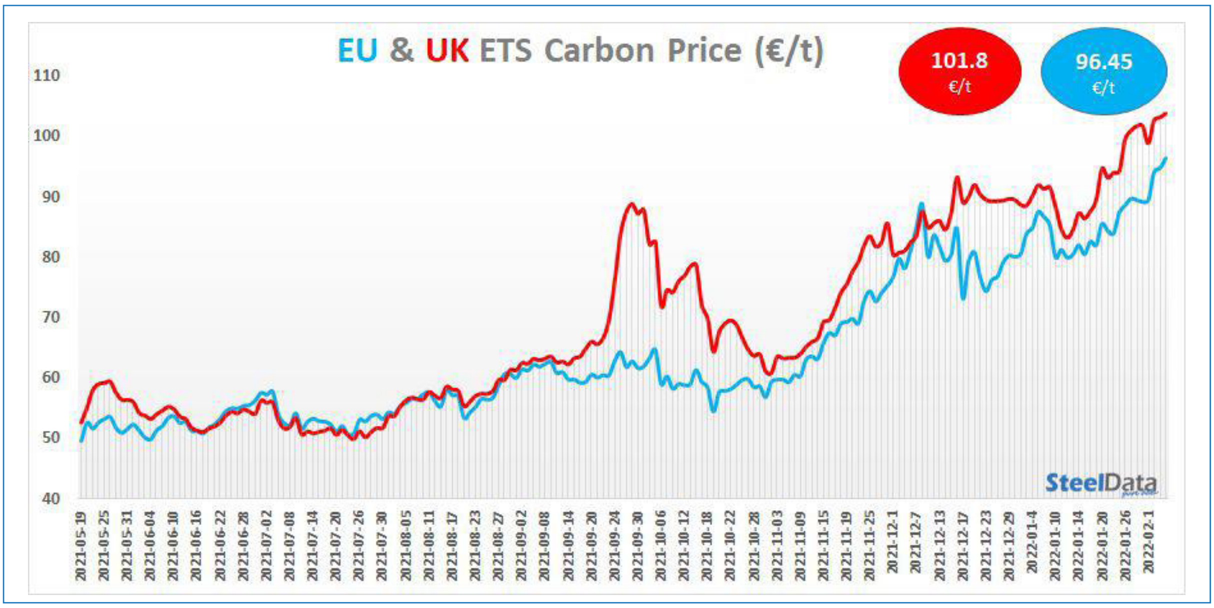


Fig. 6.26. EU & UK ETS Carbon Price (€/t CO_2)

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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 electrolysers 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[45].

6. Case Studies

The previously mentioned Midrex process and HyREX and HYBRIT case studies described further below demonstrate low CO_2 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 14th 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[46]", thus defining timetable, roadmap and construction drawings. According to the latter, the policies for the steel industry are to be the following.

[45] https://www.ilo.org/wcmsp5/groups/public/---ed_emp/---ifp_skills/documents/publication/wcms_168352.pdf

[46] 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://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

- 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_2 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_2 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%[47, 48].

6.2. Japan: COURSE 50

According to the report written by the Japan Iron and Steel Federation[49], the Japanese steel industry is poised to achieve carbon neutrality by 2050 by using domestic CO_2 reduction processing technologies and products. These notably include the drastic reduction of CO_2 in blast furnaces through the COURSE 50 project (CO_2 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_2 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.[50], the COURSE 50 objective is to reduce carbon emissions by 10% using hydrogen and by another 20% through the separation and recovery of CO_2 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[51].

6.3. Republic of Korea: POSCO[52]

In December 2020, the Republic of Korea committed to carbon neutrality by 2050 and expressed its firm intention to reduce CO_2 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_2 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_2 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) ironmaking technologies will be developed. Such technologies are based on the increased usage of high iron-bearing raw materials and H_2-rich gas in BF. Electric arc furnaces (EAF) for scrap melting are also planned to be

47 https://www.sohu.com/a/503976517_120174089

48 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

49 https://www.course50.com/en/news-en/2021/n0215_01_en/

50 X. Zhang, K. Jiao, J. Zhang and Z. Guo, Journal of Cleaner Production, 2021, Vol. 306, 127259

51 https://www.course50.com/en/news-en/2020/n1223_01_en/

52 https://www.centricabusinesssolutions.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_2 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_2 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 of 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 of 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.

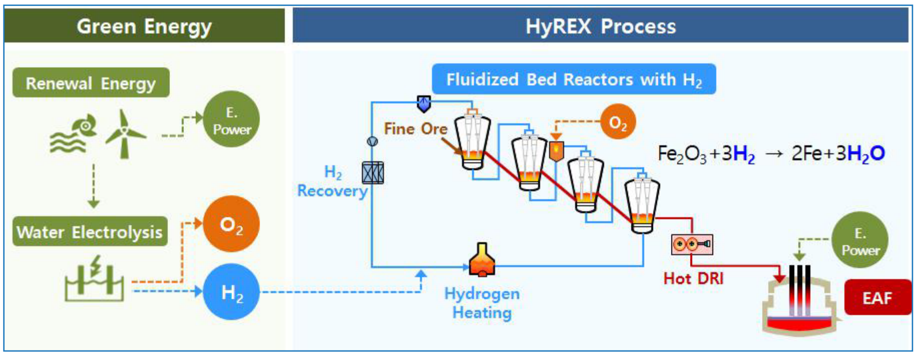

Fig. 6.27. The HyREX Process using 'green' energy
Source: POSCO. Reproduced with permission.

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[53].

[53] Video Clips introducing HyREX: https://www.youtube.com/watch?v=9u3I2lfuDnc
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)[54]

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_2 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_2 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_2) 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.

[54] Hybrit (hybritdevelopment.se): 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/

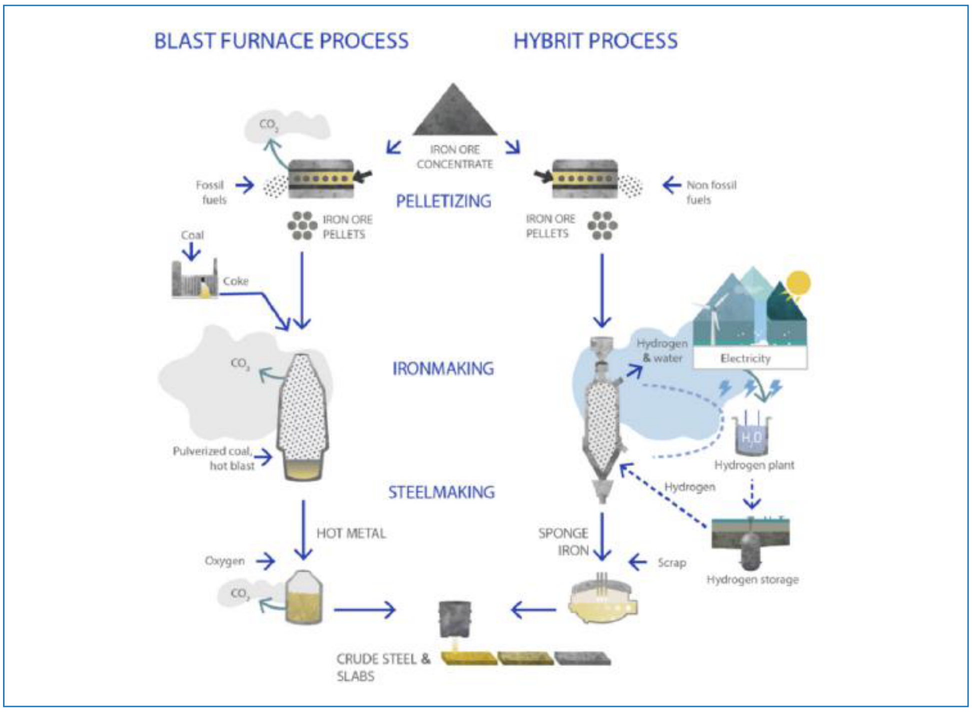

Fig. 6.28. HYBRIT flow diagram. Reproduced with permission
https://www.hybritdevelopment.se/en/a-fossil-free-future/a-value-chain-for-fossil-free-steel/

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^3. 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_2 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[55] 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[56].

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[57].

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[58].

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.

55 EVRAZ North America (evrazna.com) and Bighorn Solar Project in the USA | Lightsource bp

56 See for example: https://www.clevelandcliffs.com/sustainability/steel-as-a-sustainable-material/producing-clean-steel

57 ArcelorMittal France: https://www.recyclingtoday.com/article/arcelormittal-steel-recycling-dri-france-investment/

58 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.

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[59].

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[60].

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[61]. 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)[62].

6.6.3. H2 Green Steel, Sweden[63]

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[64]

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.

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59 ArcelorMittal Spain:
https://corporate.arcelormittal.com/media/press-releases/arcelormittal-signs-mou-with-the-spanish-government-supporting-1-billion-investment-in-decarbonisation-technologies and https://corporate.arcelormittal.com/media/press-releases/arcelormittal-sestao-to-become-the-world-s-first-full-scale-zero-carbon-emissions-steel-plant

60 TATA Steel Netherlands: https://eurometal.net/tata-steel-picks-hydrogen-dri-eaf-path-for-ijmuiden/

61 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/

62 https://www.centricabusinesssolutions.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

63 https://www.h2greensteel.com/

64 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_2 emissions: in 2020, its total direct emissions were of the order of 2.6 Gt[65], representing between 7% and 9% of global anthropogenic CO_2 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_2 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_2 emissions

Considering the urgency of reducing CO_2 emissions and the lifetime of many existing facilities, we recommend implementing every possible and economically affordable, even marginal, reduction of CO_2 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_2 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

[65] 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

BF	Blast Furnace
BOF	Basic Oxygen Furnace
CDRI	Cold Direct Reduced Iron
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
COVID-19	Coronavirus Virus Disease 2019.
DME	Dimethyl Ether
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EU ETS	European Union Emissions Trading System
EUROFER	European Steel Association, based in Brussels, Belgium
EW	Electrowinning, a ahydrometallurgical process for metal recovery
GHG	Greenhouse Gas
H-DR	Hydrogen Direct Reduction
HDRI	Hydrogen Direct Reduction Iron
HBI	Hot Briquetted Iron
HQ scrap	Pre-consumer scrap
HYBRIT	Hydrogen Breakthrough Ironmaking Technology by LKAB & SSAB (Sweden)
HyREX	A pilot plant for Hydrogen-based Reduction to be built by POSCO (Republic of Korea)
IEA	The International Energy Agency, based in Paris, France
IETF	Industrial Energy Transformation Fund (Netherlands)
IIMA	International Iron Metallics Association
LPG	Liquefied Petroleum Gas
LQ scrap	Post-consumer scrap
MIIT	The Ministry of Industry and Information Technology of China
M&E	Monitoring and Evaluation
NDC	Nationally Determined Contribution (COP 26 Paris Agreement)
NEDO	New Energy and Industrial Technology Development Organization (Japan)
OEM	Original Equipment Manufacturer
OHF	Open Hearth Furnace
OPEX	Operational Expenditure
PRC	People's Republic of China
SAF	Submerged Arc Furnace
SMR	Steam Methane Reforming
tce	tonnes of coal equivalent
Tecnocored	An ironmaking process using biomass as a reductant
TGRBF	Top Gas Recycling Blast Furnace
toe	tonnes of oil equivalent
VOC	Volatile Organic Compounds
WSA	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

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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[1, 2]. 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[3] 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.

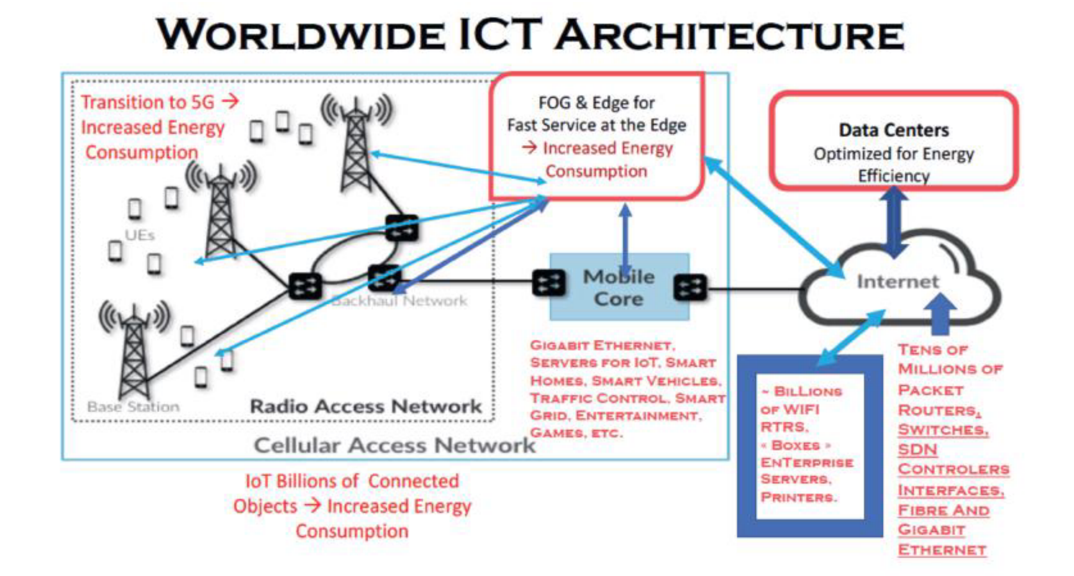

Fig. 7.1. Worldwide ICT architecture (Copyright Erol Gelenbe, member of the group of authors for this chap)

1 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

2 G. Kamiya. Data Centers and Data Transmission Networks.International EnergyAgency, Paris, June2020, https://www.iea.org/reports/data-centers-and-data-transmission-networks

3 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_2 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.

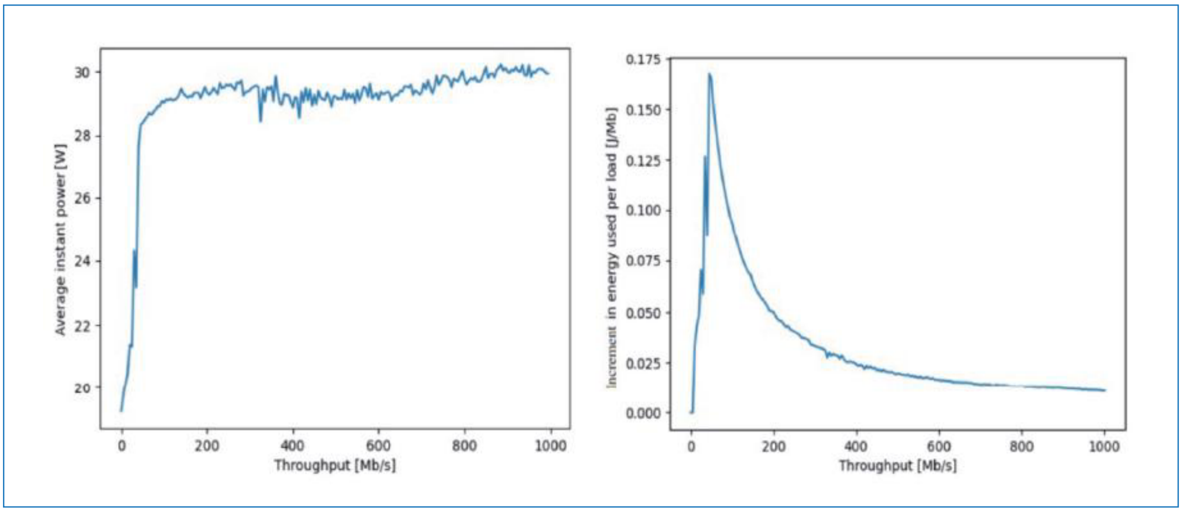

Fig. 7.2. Power consumption (Left) and Energy consumption Per throughput (Right). Characteristics of an Intel Network Unit of Computing (NUC), i.e. a small network connected PC, when used as a network router at the edge[4].

[4] P. Fröhlich, E. Gelenbe, J. Fiołka, 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, Open Access Creative Common CC BY

Given the complexity and the large amount of information exchange[5], 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_2 per kWh, the total of global CO_2 emissions thus amounts to approximately 150 million tonnes of CO_2.

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_2 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.*)[6]. 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_2 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_2 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_2 impact and further research on the different trade-offs and balances surrounding this matter is needed.

[5] 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.

[6] 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 CO2 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 CO2 (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 Kingdon	358,800
18	Italy	324,850
19	Poland	312,740
20	France	309,960

Table 7.1. Top ICT Economies and top CO_2 polluters. Reproduction of both tables with Permission.
For the table to the left "Top ICT Economies": https://www.researchgate.net/publication/341599907_And_the_Winners_Remain_CHINA_and_INDIA/figures
Hans Peter Bech, Author & Consultant, Tbkconsults.
For the table to the right "Top CO_2 Polluters": https://www.economicshelp.org/blog/10296/economics/top-co2-polluters-highest-per-capita/
Tejvan Pettinger, 19 August 2021. Source of data: World Bank CO_2 emissions (kt)

1.3. Worldwide estimate of electricity consumption by ICT and its CO_2 impact

The International Energy Agency (IEA) provided the following estimates[7] 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. Reproduced with Permission

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 [8, 9].

7 G. Kamiya. Data Centers and Data Transmission Networks.International EnergyAgency, Paris, June 2020, https://www.iea.org/reports/data-centers-and-data-transmission-networks

8 E. Gelenbe and 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

9 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_2 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[10] 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_2 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 polluters 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[11]. 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.

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10 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.

11 GSMA. Energy Efficiency. https://www.gsma.com/futurenetworks/wiki/energy-efficiency-2/

Recent reports[12, 13] 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_2 emissions as five "average" conventional cars during their lifetimes[14].

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)15 as shown in *Fig. 7.3.*

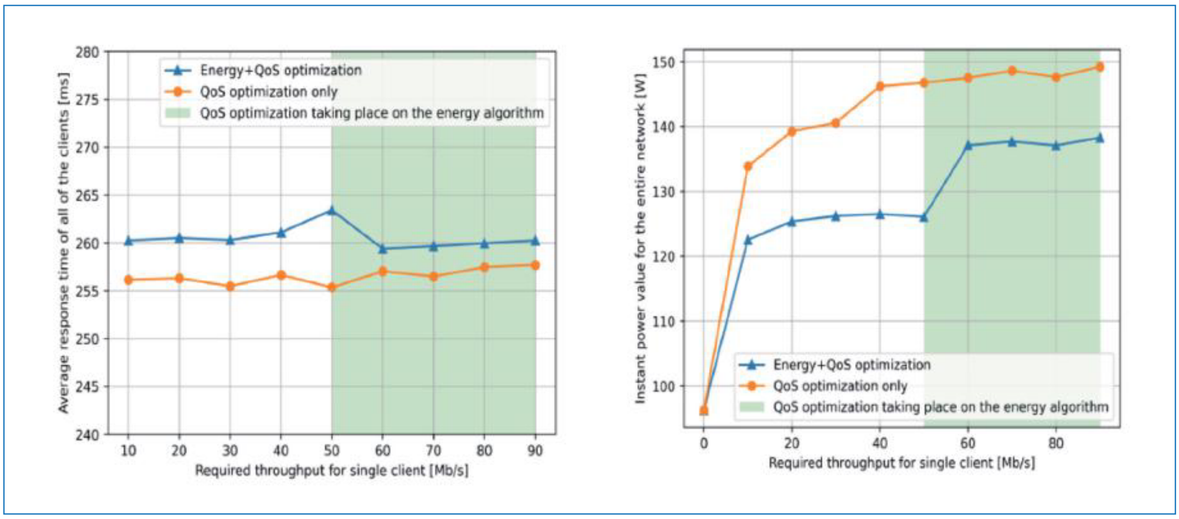

Fig. 7.3. Adaptation with reinforcement learning reduces power consumption by 10-15% at a cost of 2% reduction in average response time[16]

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.

12 Assoc. for Comp. Machinery Tech. Council: https://dl.acm.org/doi/pdf/10.1145/3483410

13 https://www.moneysupermarket.com/gas-and-electricity/features/crypto-energy-consumption/

14 https://www.technologyreview.com/2019/06/06/239031/training-a-single-ai-model-can-emit-as-much-carbon-as-five-cars-in-their-lifetimes/

15 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

16 P. Fröhlich, E. Gelenbe, J. Fiołka, 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. Reproduced with Permission

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[17]. 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[18] 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.

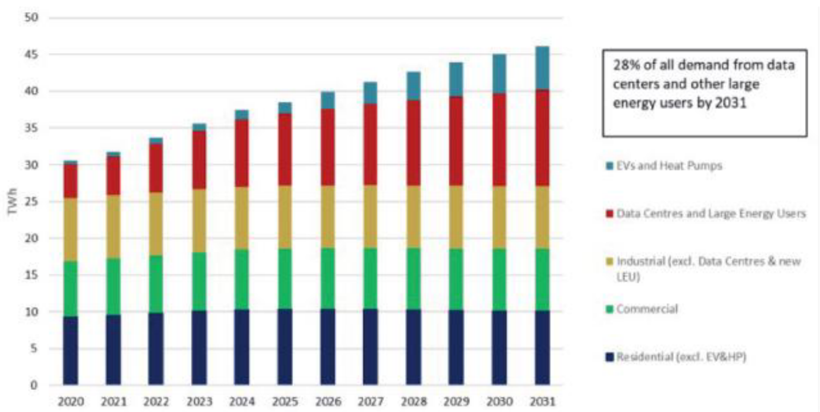

Figure 3 – Ireland Median demand scenario illustrating the approximate split into different sectors

Fig. 7.4. Annual demand split by sectors, per year (extract from EirGrid report "Ireland Capacity Outlook 2022-2031 October 2022"). Reproduced with Permission
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.

17 http://iae.ie/wp-content/uploads/2019/08/Data-Centres-July-2019.pdf

18 Tik Tok to open €600m European data centre in Ireland (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[19].

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[20].

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19 http://iae.ie/publications/europes-energy-crisis-implications-for-ireland/

20 http://www.ldescouncil.com/assets/pdf/LDES-brochure-F3-HighRes.pdf

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_2 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_2 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[21] 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_2 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_2 statistics

It is notoriously difficult to find reliable and specific data to assess the energy consumption of ICT at large[22] 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 equipement to achieve improved energy efficiency, better performance and reliability. Decommissioned equipment may often be repaired, enhanced and used in different useful contexts.

[21] 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

[22] ACM TechBrief: Computing and Climate Change, ACM Technology Policy Council, Issue 1, November 2021

Abbreviations, definitions and acronyms

5G	The fifth-generation technology standard for broadband cellular networks
Cloud	Cloud computing is a general term for anything that involves delivering hosted services over the internet
CRU	Irish Commission for Regulation of Utilities
Edge computing	Distributed computing paradigm that brings computation and data storage closer to the sources of data
EirGrid	The Irish National Electricity Transmission System Operator
FOG computing	Also called Edge computing
GHG	Greenhouse Gas
ICT	Information and Communications Technologies
IEA	The International Energy Agency, based in Paris, France
LNG	Liquefied Natural Gas
LTE	Long-Term Evolution, is a standard for wireless broadband communication for mobile devices and data terminals
NUC	Network Unit of Computing
PUE	Power Usage Effectiveness
RAN	Radio Access Network
IoT	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_2 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. Theissue 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 Pradeeep, 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, Switzeland*, 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*

KEARSLEY Elsabe, 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 Il, 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*

OGBUIGWE 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*

CHILVERS Andrew, United Kingdom, *Policy Advisor at Royal Academy of Engineering (RAEng)*

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)*

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