Technologies for the global energy transition

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Technologies for the Global Energy Transition

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1 Introduction

The United Nations Intergovernmental Panel on Climate Change 2018 Report stated, "Limiting global warming to 1.5 °C would require rapid, far-reaching and unprecedented changes in all aspects of society." In recent years, it has become clear that that scenario would require not only a transformation of our energy system in order to meet our global emissions targets, but also a rethinking of the way we control the temperature of our homes, travel around our planet, and manufacture our goods.

In order to meet this transformation by mid-century, scientists, engineers, and technical experts are needed in the crucial role of designing pathways for the decarbonization process of specific, energy-intensive sectors, notably power, industry, transport, and buildings. Fondazione Eni Enrico Mattei (FEEM) and the Sustainable Development Solutions Network (SDSN) invited more than 60 technical experts from around the world to gather in Milan in April 2019 to discuss the state of decarbonization technologies that can accelerate the global shift toward decarbonization. The outcome of that workshop, followed by an extensive external consultation and review process by a large number of scholars and stakeholders (from international agencies, academia, research centers, think tanks, non-governmental organizations, public institutions, and the private sector), was the basis of the "Roadmap to 2050: A Manual for Nations to Decarbonization by Mid-Century" (Carnevale and Sachs 2019). Some of the contents of this chapter are partially based on the work of this Roadmap to 2050.

In order to decarbonize the global economy, energy demand growth needs to be uncoupled from economic growth, and then the remaining energy demand needs to be decarbonized. This chapter provides an overview of the latest decarbonization technologies available for national governments to develop their low-emission

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development strategies as outlined in the Paris Agreement. Following the Paris Climate Agreement's aim to strengthen the global response to the climate crisis "in the context of sustainable development and efforts to eradicate poverty," the chapter is conceived on a "systems approach," aspiring to simultaneously address multiple objectives and promote policy instruments and technological solutions that can be used across sectors. The multiple objectives span decarbonization and environmental sustainability, economic prosperity (including poverty reduction), and social inclusion that leave no one behind. Needed policy instruments include public investments, phase out of subsidies to fossil fuels, market mechanisms, regulatory framework, and regulations on land use, while technological solutions address a wide range of current and emerging solutions, from smart power grids to synthetic fuels.

According to IEA (2019a), global CO_2 emissions caused by fossil-fuel combustion for energy production totaled 32.3 Gt in 2016. The first responsible has been the heat and electricity generation, with 13.4 Gt (41%), followed by transport (7.9 Gt, 24%), industry (6.1 Gt, 19%), and buildings (2.7 Gt, 8%). However, if electricity and heat generation are allocated to the relevant final sectors, industry takes the lead with 11.8 Gt (36%), while buildings and transport are comparable, with 8.6 and 8.1 Gt, respectively (i.e., 27% and 25%). The remaining emissions are related to other sectors (including agriculture/forestry, fishing, and other non-specified).

The chapter discusses the main technology options for decarbonization both of the power sector and of the three final sectors: industry, transport, and buildings. At the end of the chapter, we provide strategy and policy recommendations from a technology point of view on how to decarbonize these sectors by mid-century and of the necessity to take a systems approach.

2 The Power Sector

Electricity is the fastest growing energy vector, its demand has increased by a 3% annual growth rate since 2000 (IEA 2018), around two-thirds faster than the total final energy consumption at global scale. Worldwide electricity demand in 2017 reached 22,200 TWh according to the latest IEA's World Energy Outlook, and the future demand is expected to increase in all the different scenarios. The main reasons are an increasing access to electricity in developing countries and an increasing consumption of current users due to increased well-being. Although 840 million people still lack access to electricity as of 2017 (World Bank Group 2019), this number decreased from 1.2 billion in 2010 and is expected to further decrease.

Moreover, electrification is seen as a strong tool for decarbonization: the lower the emissions target, the higher the electricity consumption that is required. However, electrification itself is not sufficient to push toward decarbonization, since the development of low-carbon generation sources need to keep the pace with the increase of demand, which is a rather challenging task, especially in developing countries. While wind and solar have significantly ramped up, they are still representing only 6% of the total electricity generation worldwide, which remains largely dependent on fossil fuels that provide around two-thirds of the total generation, with coal holding the lion's share with 40% of the total generation. As a result, in 2017, each kWh of electricity consumed in the world resulted in 480 g of CO_2 emissions (IEA 2018).

The decarbonization of the power sector is generally associated with increasing penetration of renewable energy sources. However, especially for non-dispatchable renewables such as solar and wind, they need to be associated with other flexibility options, such as dispatchable power plants, electricity storage, grid interconnections, demand-side management, and sector coupling. Moreover, other low-carbon sources may be needed, including nuclear and fossil fuels coupled with carbon capture, utilization, and storage. The generation mix is strongly country-specific, and this will be reflected in the technological choices that will be performed to address the decarbonization targets.

2.1 Renewable Energy Sources

The main strength of renewables is to provide a solution to generate electricity with an alternative to the traditional combustion of fossil fuels, which causes significant CO_2 emissions. Different sources are available, including hydro, solar, wind, bioenergy, geothermal, tidal, and waves. The technologies used for electricity generation are at different levels of maturity, but many are showing interesting potential.

Hydropower is currently the most important renewable source for electricity generation, with more than 1 TW installed worldwide in 2016 and roughly 70% of the electricity generation from renewables (World Energy Council 2019). Hydropower includes a number of applications, ranging from base load to peak power matched with reservoir or pumped storage plants. There is still significant potential for hydro generation worldwide, although concentrated in a relatively limited number of countries with favorable morphological conditions.

This limitation is not applied to wind, which is virtually available everywhere, although with strong variations in wind consistency and strength. Wind power has shown a remarkable growth in last decades, reaching 4% of the world power generation in 2017 (IEA 2018). While the current wind farms are mostly onshore, offshore facilities are spreading, supported by the lower environmental impacts related to noise and visual impacts, together with higher capacity factors and the possibility of exploiting larger areas. A potential breakthrough technology is floating offshore wind, which is currently limited to some pilot plants in different countries but holds the potential of unlocking even larger areas.

The other source that showed a large increase in the last decade is solar energy, mainly from PV technology. The strong decrease of installation costs, driven by subsidies and manufacturing upscaling, has allowed the spread of plants both at utility scale and for final users, unlocking the paradigm of distributed generation. As of 2017, PV generated 435 TWh, with a 2% share worldwide (IEA 2018). Further cost decreases are expected (especially for inverters and balance of system, rather than PV panels themselves). A marginal share is represented by concentrating solar power (CSP), which may increase its potential thanks to higher capacity factors and the possibility of exploiting a larger flexibility in comparison with PV systems.

The main limitation of wind and solar plants is their variability, resulting in the impossibility of dispatching them when needed. In contrast, this is one of the advantages of bioenergy, which is used in thermoelectric power plants just like fossil fuels, but with a closed CO_2 cycle, meaning that the combustion emissions are absorbed by the biomass during its life. Bioenergy has traditionally been considered as carbon-neutral, but some studies are highlighting that this is not always the case, since attention must be paid on land use issues, as well as on the effect of a slow capture compared with an instantaneous emission (Hausfather 2018). Although biomass is not primarily used for power generation, it totaled 623 TWh in 2017, including solid, liquid, and gaseous bioenergy. Future developments may be focused on crops that can be cultivated in marginal areas with a specific attention on the sustainability of the entire supply chain, as well as from emerging technology like microalgae.

Other RES that have currently a marginal role in power generation include geothermal, waves, and tides. While the former has a long history and shows a narrow potential due to the limited sites available worldwide, marine energy may play a role in the decarbonization of the power sector thanks to its large potential, although the technology is currently at early stage of development.

2.2 Energy Storage and Other Flexibility Solutions

The higher the penetration of renewables, especially non-dispatchable such as solar and wind, the higher the need of technology solutions supporting the flexibility of the power system. A number of options are available, including batteries, sector coupling, networks interconnections, demand response, and traditional dispatchable power plants.

The power network balance has traditionally been obtained by dispatchable power plants, mainly based on fossil fuels. Gas-powered units have generally a higher degree of flexibility, providing higher speed and ramps. Another common option is hydro, both dam and pumped hydro, although the deployment of this option is heavily limited by the geographical and morphological conditions. The predominant role of dispatchable power plants is expected to make way for other solutions.

Among those, electricity storage through batteries is gaining momentum, both with utility-scale and behind-the-meter installations. The current upscale of lithium batteries for electric vehicles is leading to a strong cost decrease, resulting in competitive solutions in multiple countries. Electric batteries provide solutions for short-term electricity storage, i.e., up to some days, while for applications on wider time frames other solutions are required (such as the production of synthetic fuels).

An additional flexibility option that is already in operation in different countries is demand response, both in industry and buildings, which can be fostered by time of use electricity tariffs or coordinated by virtual aggregators that have the control over a large number of users. In this perspective, demand response is tightly related with a growing digitalization of the power networks, which involve the implementation of smart grids, where the increasing role of distributed generation leads to the shift from consumers to prosumers.

Sector coupling, also referred to as P2X (power-to-everything), represents the idea of coupling the electricity system with other sectors (heating and cooling, mobility, desalination) or to generate other energy carriers (gases and liquids). This option is increasingly seen as an opportunity to accommodate the excess of power generation from RES, especially in countries with high penetrations of wind generation. In some cases, sector coupling can also be operated as electricity storage, if the technology allows a bi-directional operation, such as power-to-gas coupled to fuel cells or vehicles-to-grid.

Finally, network interconnections should not be overlooked, since they are an important flexibility solution, both at local and international levels. The connection of a larger pool of both users and generation units can support a better matching of demand and supply, by decreasing the limitations and the bottlenecks that may be related to the transmission and distribution infrastructure.

2.3 Other Generation Sources

While much attention is put on renewables, which are necessary to reach a fully sustainable power generation in the long term, other options may be needed in the short term to reach a faster decarbonization of the sector. In particular, natural gas is seen as a promising solution to facilitate the phase out of coal power plants, especially in developing countries. However, some experts fear a potential lock-in of fossil-fuel technologies. Another source that is not yet object of consensus is nuclear, which allows generating low-carbon electricity but with other potential environmental impacts.

Natural gas is seen by many as a potential bridge fuel by temporarily offsetting the decline in coal use. Others have contended that such option is incompatible with the current climate targets and that methane leakage from natural gas systems (especially upstream) may eliminate any advantage that natural gas has over coal (Levi 2013). A transition from coal to natural gas power generation has already happened in the US, mainly due to the rise of shale gas production, but with the effect of lowering the international price of coal and shifting its use to other countries. China has partially seen a similar shift, mainly caused by the need to limit the local pollution in large cities. However, natural gas will need to face a strong economic competition with both coal and renewables, and the investment in plants and networks that will operate for a limited time lead to the fear of stranded assets for investors.

Nuclear power has not seen significant improvements in the last two decades, resulting in a decrease of its share in power generation from 17% in 2000 to 10% in 2017 (IEA 2018), also due to the worldwide economic recession and to the concerns raised by the Fukushima Daiichi nuclear disaster that had consequences on the nuclear policies of several countries (including Japan, Germany, and Italy). However, most countries with nuclear power or with plans to add nuclear power to their energy mix have maintained an interest in developing the technology. In several cases, visible delays in nuclear implementation have resulted from safety reviews and resultant required actions (Nuclear Energy Agency 2017).

In addition to current nuclear fission technology, potential developments are expected from small nuclear power reactors, driven by the desire of reducing investment costs as well as decreasing the importance of centralized power generation at large sites. There seems to be a renewed interest in nuclear fusion, which is attracting private investors through different technological options (The Economist 2019). However, all of these options are still at very early stages, since no solution has yet reached a net energy gain (i.e., they have to produce more energy than they consume), and therefore any possible success will have consequences on a long-term horizon.

2.4 Carbon Capture, Utilization, and Storage

Another technological solution that may play a significant role in the decarbonization of the power sector is the carbon capture, utilization and storage (CCUS), aiming at complementing power plants based on combustion, both for fossil fuels and eventually for bioenergy (BECCUS), to reach net negative emissions. Different technologies and concepts are available.

The first projects related to CCS were aimed at exploiting the carbon dioxide to enhance oil recovery in depleted reservoirs. Since the first large-scale facility, which dates back to 1972, almost one hundred CCS facilities and nine test centers worldwide have started up or begun construction (Global CCS Institute 2018). These projects generally involve the post-combustion separation of the CO_2, with removal efficiencies around 90%, and require additional power consumption and a dedicated infrastructure for the transport of the gas to the storage site. Transport and storage risks are among the causes leading to a low public acceptance of these projects, which appears to be higher when carbon dioxide is reused instead of sequestrated (Arning et al. 2019).

Many alternative solutions are being proposed for CO_2 utilization. Sometimes referred to as carbon-to-value, CCU includes the multiple technologies that allow to recycle the carbon dioxide stream obtained by flue gases or air to manufacture a range of products, including cement, carbonates, chemicals, plastics, and synthetic fuels. The aim of these processes is to find an alternative to CCS, by overcoming the concept of burying carbon emissions underground and providing effective value by creating market products that would have consumed other resources for their production. In some cases, e.g., when producing fuels, the carbon dioxide is released again into the atmosphere, but the entire cycle is (almost) carbon-neutral. There is a growing interest in CCU applications worldwide, and some companies are already providing commercially competitive solutions, although often at limited scale.

While the previous concepts are generally coupled to the combustion flue gases of thermoelectric power plants, another technology still in early maturity is gaining interest in the scientific community: direct air capture (DAC). The idea of DAC is to use specific solutions, including membranes, to capture the CO_2 directly from the concentration in the air. This would allow a broader flexibility in locating the facility. One of its main challenges is related to its significant energy consumption, although experts are confident it can become cost-competitive with other CO_2 capture technologies if massively deployed (Fasihi et al. 2019). Another limitation appears to be the rate at which this technology can be scaled up (Realmonte et al. 2019).

3 The Industry Sector

The industrial sector is composed of a large variety of activities, which have different purposes and characteristics, and for which specific decarbonization solutions and technologies are required. If heat and electricity emissions are allocated to the relevant final sectors, industry is the single final sector with higher CO_2 emissions, with 36% of the 32.3 Gt of emissions estimated for 2016 (IEA 2019a). The emissions in industrial applications include both the direct emissions during the processes, and the indirect emissions caused by the fuel combustion to provide the energy required by the processes.

Decarbonization strategies in industries include three main areas: actions on the demand/reuse of products and materials, energy efficiency in the industrial processes, and different sources in the energy supply. The first area includes both actions devoted to decrease products demand and increase recycling both for industrial stakeholders and for final consumers. The energy efficiency measures in industrial processes involve a number of technologies that are already available, but that are not economically viable due to the absence of specific incentives to support low-carbon solutions (e.g., carbon tax). Finally, the use of different sources for energy supply in industry may include electricity and hydrogen produced from RES, sustainable biomass, or fuel combustion coupled with carbon capture systems.

A general concept for different industrial sectors is that there are currently no purely technological limitations blocking major decarbonization routes. The barriers are economic and not technological: for the most part, we have the technologies today, but they are expensive. Future technological advancements might very well reduce those economic barriers (Carnevale and Sachs 2019). An additional aspect related to economics is represented by the high cost of production plants, resulting in long average lifetimes (in some cases up to 50 years). Therefore, since the turnover is limited, the implementation of new systems would require some time in existing plants and would need to be economically competitive for new plants. Moreover, large industrial facilities are heavily integrated, and therefore a retrofit of a part may require the adaptation of the other units, resulting in the need of a systemic approach.

This section will mainly be devoted to three main industrial applications, due to their major contribution for carbon emissions: cement, steel, and chemicals. Some of the solutions that will be presented can also be applied to other industries. A final paragraph will be devoted to the technologies related to Internet services: although they are not usually considered as an industrial sector, their dramatic growing in the last decades calls for attention on the increasing energy consumption they require.

3.1 Cement

The share of global CO_2 emissions deriving from the cement industry is about 5%. More than 50% of these are process-related and cannot be avoided (Markewitz et al. 2019). These emissions are caused by the manufacturing of cement from limestone, since the heating of limestone ($CaCO_3$) releases carbon dioxide to produce CaO, the primary component of Portland cement. These emissions are currently dispersed into the atmosphere, since there is no incentive or regulation to support alternative solutions. Since the process emissions represent the most significant share in the cement industry, substitution of clinker with other materials for cement production (blended cement) reduces carbon dioxide emission significantly (Nidheesh and Kumar 2019). Another option, without modifying the chemical process, would be to install carbon capture systems to avoid those emissions, although some technical challenges are related to the very high temperatures at which those processes occur.

Other actions that can support a reduction of the CO_2 emissions include the use of dry kiln instead of wet kiln, efficient kiln drives, low-pressure drop cyclones for suspension preheaters, heat recovery for power generation, kiln shell heat loss reduction, kiln combustion system improvements, seal replacement, oxygen enrichment, conversion to reciprocating grate cooler for clinker making in rotary kilns, adjustable speed drive for kiln fan for clinker making in all kilns, indirect firing for clinker making in rotary kilns, modern power management systems, and use of modern clinker coolers (Fellaou and Bounahmidi 2017). Moreover, indirect emissions are caused by fossil-fuel combustion for heating purposes, which can be substituted by other low-carbon sources, mainly biomass.

3.2 Steel

The production of iron and steel is not only associated with fossil-fuel combustion CO_2 emissions, but it includes also process emissions. Iron and steel products are basic materials at the core of modern industrial systems, additionally being essential also for other decarbonization options like hydro and wind power (Mayer et al. 2019). Iron and steel production is estimated to cause 25% of the global CO_2 emissions from the industrial sector (Serrenho et al. 2016). While continuous process improvements and retrofitting measures have led to a relative decoupling of emissions from fuel combustion in last decades, especially in Europe, process emissions are essentially unavoidable under current conventional best-available technologies (Mayer et al. 2019).

To reach long-term decarbonization targets, multiple studies have concluded that a strong decline in CO_2 emissions is achievable only by a combination of BATs and CCS, or with a major decline of the sector's output. This latter solution appears unlikely in the medium term, unless alternative materials become viable, such as polymers for the automotive applications or wood for construction. Another possibility would be the scale-up of steel scrap recycling, although it is not expected before some decades and the quality of the final product may not reach the required standards.

The current most diffused iron and steel production routes are the blast-furnace basic-oxygen-furnace route and the route of carbon-based direct reduced iron (which is fed into an electric arc furnace), representing 71.6% and 28.0% of global steel production, respectively, in 2017 (World Steel Association 2018). Two promising emissions-free breakthrough alternatives are the route of hydrogen-based direct reduced iron (fed into an EAF) and the plasma-direct steel production route. However, since they both rely on electricity consumption, a low-carbon power generation mix is essential to limit the indirect emissions.

3.3 Chemicals

Within the industrial sector, the chemical industry is one of the largest energy users, accounting for 12% of global industrial energy use (Sendich 2019). The chemical industry is usually divided into basic chemicals that are the basis for other products, and specialized chemicals, including medicine, soap, and paints. Basic chemicals, or commodity chemicals, generally require significant energy for their production, but due to their large-scale production they are sold at low prices. They include raw material gases, pigments, fertilizers, plastics, and rubber. Fossil products (mainly natural gas and oil) are used to produce chemicals both as fuels and feedstocks. The energy production is mainly necessary for process steam and for equipment (e.g., pumping), and the largest feedstock use is required by the petrochemical industries.

The top five commodity chemicals with both the largest production volume and energy consumption worldwide are ammonia, ethylene, propylene, methanol, and benzene/toluene/xylene (BTX). All of these chemicals require energy for their synthesis, and in some cases also hydrogen is involved as a feedstock. While current hydrogen production is mostly performed through natural gas steam reforming, mainly for economic reasons, water electrolysis is a mature technology, and may be adopted if supported by carbon pricing policies. Some of these chemicals, particularly methanol and ammonia, may be used as synthetic fuels in a low-carbon energy system if produced by renewable electricity, leading to a closed carbon cycle.

Some technological solutions related to the chemical processes include the possibility of exploring electrochemistry, since there are many possible routes for electricity to drive a chemical reaction (Schiffer and Manthiram 2017). Electrification may allow chemical reactions at lower temperatures, supporting the development of smaller units distributed in locations with high availability of renewables for power generation. An additional advantage would be the decreasing distribution costs. Finally, electrochemical reactions facilitate the products separation, which can be an energy-intensive step in the current technological processes.

Electrification of the chemical industry may be integrated into broader trends in modular and local manufacturing that have been enabled by robotic automation and additive manufacturing methods to support a new paradigm of a fully integrated, decarbonized, local manufacturing that starts with renewable resources and ends with desired commercial products (Schiffer and Manthiram 2017).

3.4 Information and Communication Technologies

Although not traditionally included into the industry sector, the potential growing rates of the power consumption of the information and communication technologies (ICT) sector may reach important shares, and therefore it should be considered into the analysis of future energy systems. The energy consumption of the sector is limited to electricity, thus more easily manageable in the hypothesis of a low-carbon power mix, but dramatic rises of power demand with respect to the forecasted scenarios may have an impact on the deployment of RES power plants.

Andrae and Edler (2015) calculate that the ICT sector will represent 21% of global electricity consumption by 2030, reaching 8,000 TWh from a base of around 2,000 TWh in 2010. Two additional scenarios are presented by the authors, with relative power consumption ranging from 8 to 50% of global electricity use by 2030. The International Energy Agency (IEA 2017), provides some figures for the power consumption of communication networks (185 TWh in 2015) and data centers (at 194 TWh in 2014), which together represent around 2% of the global electricity consumption. A moderate growth in the energy consumption of data centers of 3% by 2020 is expected, but there is a greater uncertainty for the estimation of future consumption for networks, with scenarios varying between growth of 70% and a decline of 15% by 2021 depending on trends in energy efficiency.

In general, it is not clear if the current positive trends in energy efficiency, particularly for data centers, will be able to compensate the dramatic increase of data demand for the users (Morley et al. 2018), in particular, if future technologies will be massively adopted, including smart devices and automated vehicles. The growth of Internet traffic is the combined results of multiple phenomena: the increase of Internet users, the rise of the average devices per user (there will be 3.6 networked devices per capita by 2022, up from 2.4 networked devices per capita in 2017, Cisco 2019), as well as the constantly increasing speed and contents that are available for the users. These aspects result in an exponential growth of Internet traffic, with global traffic flows rising from 100 GB per second in 2002 to 26,600 GB per second in 2016, and the volume of traffic is expected to nearly triple within the next 5 years (Cisco 2019).

Finally, an aspect that deserves attention is the daily pattern of ICT consumption, since the trends suggest that the increase of Internet use during peak hours is rising even faster, driven by the video streaming (Morley et al. 2018). For this reason, particular attention should be paid to the management of peak electricity demand, which may become most critical than in current electricity networks. Decarbonization strategies should deal with Internet-related energy demand as it develops, rather than allowing it to become a “problem” that will be harder to tackle once data-intensive services are more thoroughly embedded in normal, everyday life and thereby “locked in” (Morley et al. 2018).

4 The Transport Sector

The total final energy consumption of the transport sector reached 2.8 Gtoe in 2017 (IEA 2018), almost 29% of the total, and 92% is represented by oil products, although they account for less than 50% of the growth in demand over the previous year. Mobility demand is showing a constant increase at global level, which is expected to continue for the next three decades. Both passenger and freight transport is expected to increase nearly threefold between 2015 and 2050 (ITF 2019), based on the current path. The reduction of CO_2 emissions in transport needs a combined approach, tackling both a limitation of the demand and the deployment of low-carbon alternative technologies as well as compensation measures.

This section will present the main technological options that are available in the four main segments of passenger and freight transport, i.e., road, rail, aviation, and shipping. Currently, three-quarters of the final energy consumption in transport is due to the road segment, with roughly 10% each to aviation and shipping and just 2% to rail, also thanks to its higher energy efficiency compared to other modes (International Energy Agency 2016). These shares have remained rather unchanged in the last three decades, although the total transport energy demand is more than doubled.

4.1 Road Transport

Road transport is probably the most various segments of the transport sector, ranging from passenger cars, buses, and two-wheelers to heavy trucks for freight. The current situation is seeing a predominance of internal combustion engine (ICE) technology, based on oil products and on a limited share of alternative fuels, including biofuels and natural gas. The two main potential alternative powertrains are based on electricity, either by its direct use through its storage supported by on-board batteries, or through its conversion from hydrogen thanks to a fuel cell. The opportunities and challenges of these technologies are related to a number of aspects, including cost, range, flexibility, reliability, performance, and charging time.

There is an increasing interest in electric vehicles (EVs) worldwide, especially for passenger light-duty vehicles (LDVs). EVs generally include multiple technologies, from hybrid EVs (HEVs), which have both a traditional ICE powertrain and an electric engine (but usually no possibility of directly charging from the external grid), to battery EVs, which are fully electric. An intermediate technology is the plug-in hybrid (PHEV), which is a hybrid vehicle with a larger battery and the possibility of connecting to an external power source. Finally, fuel-cell-powered EVs (FCEVs) are often grouped in the category of EVs, although they are basically running on hydrogen to supply the electricity needed by the vehicle.

The penetration of EVs in the global market currently remains marginal, although significant improvements are being made in the last years. The global EVs car fleet reached 5.1 million in 2018, almost doubling the number of new EVs sales (IEA 2019b), but compared to a total car fleet around 1 billion. The world largest market remains China, followed by the US and Europe, and the largest share of EVs market share is in Norway, where in 2018 EVs reached 46% of the new vehicles sales. However, electricity penetration in passenger transport is going beyond cars, especially in China. The country hosts the vast majority of the estimated 300 million of electric two-wheelers in the world (IEA 2019b), while electric buses reached a world fleet of around 460,000 vehicles, with 100,000 new sales in 2018.

The deployment of EVs requires a parallel development of a proper charging infrastructure, whose capillarity is essential to support the use of EVs. In particular, a total of 5.2 million charging points for LDVs are estimated worldwide, mostly slow chargers installed at private houses and workplaces, including an estimated 540,000 public chargers, of which 150,000 fast chargers (78% in China).

The limitations of EVs deployment are mainly related to the limited available range due to the low energy density of batteries, together with the high duration of charging and the current limited availability of charging points. The investment costs are currently higher than for ICE cars, but a massive upscaling of EVs manufacturing may lead its future cost to be in line with traditional vehicles. Moreover, expected improvements in batteries technology may also increase the performance of EVs. The chicken-and-egg problem of vehicles and charging infrastructure deployment may be currently slowing down the adoption of EVs, especially in Europe.

The limitations related to BEVs are among the reasons that may lead to the adoption of hydrogen-powered vehicles, which promise longest ranges and shorter charging times. However, the generation, compression, and use of hydrogen lead to an increased energy chain leading to a lower system efficiency when compared to batteries. This aspect may not be too critical in terms of emissions as long as the electricity is produced by RES, but the need of additional power generation should be carefully taken into account. Other issues related to hydrogen are the transportation and the installation of a proper refueling infrastructure.

An alternative pathway for road transport decarbonization is related to biofuels (e.g., biodiesel, biomethane) or to synthetic fuels (e.g., methanol) supported by electricity generation from RES. These solutions have the advantage of exploiting the existing powertrains as well as distribution infrastructures, although their limited availability would suggest that their use may be prioritized to transport segments that are harder to electrify (i.e., aviation and shipping).

Finally, heavy trucks for freight transport have different requirements than LDVs, since their higher size and required ranges may deter the use of electric batteries, although some companies are currently evaluating their technical feasibility. The most probable alternatives include hydrogen-powered trucks or electric road systems, in which the vehicles are constantly supplied with the required electricity during the travel on highways. These systems may be integrated with different powertrains (e.g., batteries, hybrid, or hydrogen) to enhance their flexibility and limit the need of a capillary power infrastructure outside of the main roads.

4.2 Rail Transport

Rail networks carry around 8% of the world's motorized passenger movements and 7% of freight transport, but account for only 2% of energy use in the transport sector, thanks to their high efficiency (IEA 2019c). Rail transport includes conventional railways around and between cities, high-speed railways and urban networks (including subways and tram). The majority of passenger transport on conventional railways is located in Asia, with India accounting for 39% of the total, followed by China with 27%, and Japan with 11%. Today China accounts for about two-thirds of high-speed rail activity, having overtaken both Japan (17%) and the European Union (12%). The regional distribution of urban rail activity is more even; China, European Union, and Japan each have around one-fifth of urban passenger rail activity.

Rail transport is currently the most electrified transport mode worldwide, although with different levels depending on the area. Considering conventional railways, three-quarters of passenger rail transport and almost half of all freight rail are electric (IEA 2019c), the remainder being powered by diesel trains. High-speed rail and urban rail are completely powered by electricity.

As a result, the challenges for rail transport decarbonization appear lower than for other modes, as the options are clear and already available. Efforts are needed to further improve the power infrastructure in some railways that are not yet electrified, together with the extra-sector improvement of the share of power generation from renewables. However, the electrification of railway lines with low utilization factors is often not economically affordable, and therefore other technologies may play a role, including battery-electric trains and hydrogen fuel cell trains.

Potential alternatives to high-speed railways include maglev (magnetic levitations) and Hyperloop concepts. Maglev trains are already in operation in six locations in Asia, but the only train that is operating at a speed higher than the normal high-speed trains is the one connecting Shanghai City center with the airport, reaching a top speed of 430 km/h over the 30 km of its length. Another project currently under construction in Japan plans to connect Tokyo and Nagoya, but the benefits provided by increased speed come at the cost of a four to five times higher energy consumption in comparison with the current high-speed train connecting those cities. Another alternative technology, the Hyperloop, is based on a low-pressure tube in which a passenger or cargo pod is operated through an electromagnetic propulsion system.

According to some feasibility studies, this technology could be more efficient than the current high-speed trains, but there are not yet any real figures from services in commercial operation.

Further actions are possible in the optimization of the demand and logistics, especially in freight, and the improvement of the performance and energy efficiency of railways. These solutions may include the implementation of on-board energy recovery devices (including regenerative braking and energy storage), as well as the use of lighter materials and a decreased use of energy-intensive power electronics.

4.3 Aviation

Aviation is among the most critical transport segments, due to its constantly increasing passenger demand, especially for long-haul flights, and the high energy density that is required. Demand for domestic and international air transport combined will rise from 7 trillion passenger-kilometers in 2015 to 22 trillion in 2050, according to (ITF 2019). Moreover, since air travel is a highly regulated environment, the access to innovative technologies is strongly related to the policies implementation.

The most promising pathway for air transport decarbonization is the development of advanced sustainable jet fuels, either by incorporating biofuels, or by the use of synthetic fuels based on power generation from RES. The blending of biofuels with the current fossil-based products may provide the possibility of gradually integrating low-carbon solution in the existing system, without the need of major changes in the current fleet, which usually has a renewal rate around 30 years. However, to match the requirements of existing certifications, the fuels need to provide high energy density and low freezing temperatures, which is rarely the case for available biofuels. Thus, a blending with fossil fuels is currently required to meet those strict standards.

The electrification of short- and medium-haul flights is being evaluated by different manufacturers, but major hurdles remain related to the energy density provided by the current batteries. Moreover, the largest part of air travel demand worldwide is related to long-haul flights, since travels shorter than 600 nautical miles (that would be the target of potential electric aircrafts) currently represent half of the departures but only 15% of the total fuel use (Schäfer et al. 2019). Hybrid technology may enter the market soon if it proves to bring economic advantages, and the combination with biofuels may help in reaching the decarbonization goals.

Lastly, energy efficiency measures are necessary to compensate the expected increase in demand. These solutions include the use of innovative materials such as advanced composites and airframe metal alloys, with lower weight and improved performance, and the development of new plane designs. As in any sector, energy efficiency is usually the most effective measure to support decarbonization, and available solutions should be always prioritized before thinking of a sustainable energy supply.

4.4 Shipping

The other transport segment that shows severe challenges for decarbonization is maritime shipping, especially for long-haul freight transport. Solutions and opportunities differ depending on the range and the purpose of the trip.

Short-haul naval shipping for freight and passenger transport, especially in inland waterways, is already seeing an evolution toward electrification in some countries. The ships operation on fixed routes allows a better planning of the battery size as well as the management of charging during the load and unload of the ship. Electric ferries are already in operation in Denmark and Norway, and different technologies are under evaluation, including hydrogen fuel cells (Norled 2019) and flow batteries (Valentine 2018).

For long-haul freight maritime transport, which represents the largest share of fuel consumption in the sector and totally relies on oil-based bunker fuel and diesel, some potential alternative fuels are under evaluation. The current regulations limiting pollutant emissions in some areas are pushing toward cleaner fuels, including liquified natural gas (LNG). Other low-carbon options, although not yet commercially available, are hydrogen or ammonia produced through electricity from RES. Ammonia has higher volumetric energy density than hydrogen and more practical storage temperatures and pressures, and its production requires less energy than other synthetic fuels like methanol or ethanol (Laursen 2018). However, for the development of all these alternative fuels, a dedicated infrastructure is required, both for their production and distribution and for their supply in the ports worldwide, since a diffused availability of fuel supply is at the basis of its use for long-haul freight.

Besides the supply technologies, energy efficiency measures can be implemented to decrease the energy demand of shipping. These include the use of lighter materials, the slender design, the decrease of friction (air lubrication, hull chemical coating), on-board waste heat recovery, wind assist, or exploitation of renewables sources with on-board devices such as kites (Traut et al. 2014). Moreover, a better electrification of ports and the availability of power supply for boats would allow the combustion of fuels for on-board power demand during the loading/unloading operations.

5 The Buildings Sector

Buildings floor area in the world is currently estimated at around 223 billion m^2, and it is expected to grow to 415 billion m^2 by 2050 (Dean et al. 2016). The largest increase is expected from Africa, in line with the expected increase of population which may reach a total of 2.5 billion people in the continent by 2050 (United Nations 2019). Buildings are the final sector with highest final energy consumption at global scale, with 3.05 Gtoe as of 2017, although energy efficiency measures have limited its energy demand growth in last decades (IEA 2018). Moreover, an additional impact is related to the embodied energy, i.e., the energy required for materials and construction, although these impacts are generally included into the industry sector.

The strong push from growing population and increasing income levels in emerging economies and developing countries represent the main drivers for building stock rise, leading to a potential increase of energy consumption in the sector reaching 50% by 2050 if no action is taken (Dean et al. 2016). In the 2010–2017 period, energy consumption increase (+5%) has been lower than the increase of floor area (+17%), thanks to the improved energy efficiency in new buildings and in renovations. Electricity (+15%) and renewable energy sources (+14%) contributed more than natural gas (+5%) to the substitution in final energy use of less-efficient coal-based technologies (−8%), while other fuels (oil and biomass) remained almost stable. Natural gas and electricity constitute the main energy source in OECD countries, while non-OECD countries still mainly rely on biomass and coal, with slow shifting to electricity and gas (Carnevale and Sachs 2019).

Energy consumption in buildings is related to multiple aspects and services, including heating and cooling, lighting and appliances. Moreover, although the majority of buildings are related to housing purposes, other applications with specific energy demand needs and patterns include shops, offices, schools, hospitals, etc. The amount and type of energy demand is related to the specific activity and the occupancy schedule and density for each building. Some services are also strongly dependent on external weather conditions, both for temperature and solar radiation, and strong variations occur on a geographical and chronological basis.

This section will present the main decarbonization options for buildings, by considering heating, cooling, and electricity demand. In comparison with other sectors, energy efficiency measures are of utmost importance, and although many actions have already been undertaken, especially in developed countries, there is still a huge potential for energy savings and rational energy use in the building sector.

5.1 Space and Water Heating

Space heating is particularly significant in temperate and cold climate regions, with a strong seasonality imbalance between winter and summer. Also domestic hot water production is generally higher in those regions, although it shows a more evenly distribution both across the world regions and the months of the year. Fuel consumption represents roughly two-thirds of the total final consumption in buildings as of 2017 (IEA 2018), of which less than half is from renewables (mainly traditional biomass used for heating and cooking), and therefore significant measures are required to address this aspect.

The most impactful actions for space heating decarbonization are related to buildings insulation, both for building envelope and for windows. An increasing number of countries worldwide is adopting buildings energy performance regulations, with stringent limits for both new buildings and renovations. However, it has to be reminded that the current renovation rate of buildings worldwide is around 1%, but to reach a total decarbonization by 2050 an increase up to a 3% rate would be necessary (Dean et al. 2016).

Considering energy supply, the most promising solution to substitute fossil fuels is the switch toward heat pumps (HPs), which are a mature and efficient technology for space heating, especially coupled with low-temperature heating systems (such as radiant floors or low-temperature radiators). Heat pumps are based on the principle absorbing heat to a low-temperature heat source (which is usually the outdoor air or the ground) and supplying heat at a higher temperature, thanks to an additional energy input, usually electricity (although gas- or heat-powered HPs are available). The coefficient of performance (COP) of the current heat pumps, i.e., the ratio between the useful heat supply and the electricity consumption, is generally between 3 and 5, depending on the working conditions. Ground-source heat pumps have generally a better performance thanks to the higher temperatures of the ground compared to outdoor air, especially in winter.

While heat pumps are an interesting and promising solution, it has to be observed that the electrification of space heating should be deployed in parallel with the decarbonization of the power sector. The strong seasonality of heat demand may become an issue if the future power mix would be strongly based on solar energy, since the generation pattern would not be well-matched with the heat demand profile (Jarre et al. 2018). Therefore, proper storage strategies would be needed, both on a day/night basis and on a weekly or seasonal basis to compensate the weather fluctuations (both programmed and unexpected).

An alternative solution for the heating sector decarbonization is district heating (DH), which is a mature technology for the energy supply to buildings in dense areas. DH systems are based on a centralized heat generation facility, from which heat is supplied to the users through a network of insulated pipes. While traditional DH systems are based on fossil-fired cogeneration units, the potential upgrading toward low-temperature RES-based DH systems can be obtained through the integration of solar energy, heat pumps, waste heat, and biomass. Some technical challenges remain, but DH can play a significant role in densely populated areas, also integrating distributed heat sources, developing smart thermal networks. Moreover, DH systems can be integrated with power networks through sector coupling, to exploit the availability of excess electricity from RES to generate heat to be stored or directly supplied to final users.

Finally, a limited role may be played by other renewable sources, mostly local wood biomass and solar thermal. Rural areas with a low population density and severe climate conditions may benefit from the use of local wood biomass, which can be used for high-temperature heat generation. Wood biomass is already used in many world regions, although in developing countries it is often used for cooking in low-quality appliances, leading to severe problems for safety and pollutants emissions. On the other hand, the use of local biomass in modern stoves is already a sustainable and low-carbon solution to substitute the use of fossil fuels in many rural areas. Space heating can also be integrated with solar collectors, especially in middle seasons and in climates that are not showing extreme conditions. However, solar thermal is usually mostly used to provide domestic hot water, especially in summer. Among its main advantages, there are the low cost, the simple system configuration, and the relatively high efficiency (up to 70–75% of the solar radiation can be converted into useful heat).

5.2 Space Cooling

While space heating has traditionally been a significant cause of energy consumption in buildings, the role of cooling is progressively increasing worldwide. This growing trend is expected to continue, sustained by the climate change and the growing per-capita income in developing countries. Current cooling technologies are relatively limited, and the large majority of cooling worldwide is supplied by distributed electricity-powered chillers, with some few exceptions including district cooling networks or solar cooling units.

The most impactful actions to limit energy consumption would be the limitation of the rising cooling demand. This could be obtained through building design strategies aimed at minimizing the cooling needs (cool roofs, shading systems, night ventilation), integrated with solutions for the free cooling when the outdoor conditions are favorable. These solutions would be even more impactful in hot climate countries, where cooling demand is particularly high. Non-residential buildings show a significant potential for energy savings through a proper energy management, since they often operate cooling equipment with very low set point temperatures and without a proper attention to limit the flow of cooled air to the outside.

Considering cooling supply, the installation of high-efficiency chillers and their proper operation could lead to significant energy savings. Attention must be paid on maintenance operations, especially for air filters, to avoid unnecessary additional energy consumption. In specific contexts, the use of high-efficiency district cooling networks or solar cooling units may provide performance improvements with respect to common solutions.

5.3 Lighting, Appliances, and Cooking

Besides heating and cooling, there is an increasing energy demand in buildings related to power supply for lighting and appliances, mainly driven by the diffusion of technologies providing multiple services to the users. As long as electricity consumption is concerned, there is a huge difference across developed and developing countries. In the former, the increased integration of houses with digital technologies and the Internet of Things (IoT) may lead to an optimized supply and use of services, but dramatically increasing the power demand of households. At the same time, developing countries are still facing severe problems of energy access, especially in Africa, where many buildings are able to power any appliance or electric lighting system. Universal energy access will increase the living conditions of million of people, and at the same time boost the installation of appliances that will lead to higher power consumption also in existing buildings. For this reason, it is important to ensure regulations that require high standards in energy efficiency both for lights and other appliances.

Another cause of energy consumption in residential buildings is cooking. While in developed countries most houses have access to gas- or electricity-fired cooking systems, the majority of the world is still relying on biomass or coal. While burning local biomass has a limited impact on CO_2 emissions, thanks to the closed CO_2 cycle, it has severe consequences for the indoor air quality and for safety. For this reason, it is important to support the deployment of clean and efficient cooking technologies. Induction cooking is providing higher efficiencies than traditional electric and gas cooking, and its deployment may play an important role toward decarbonization.

6 Conclusions: Strategies and Policy Recommendations

Following the Paris Climate Agreement's aim to strengthen the global response to the climate crisis "in the context of sustainable development and efforts to eradicate poverty," it is necessary to use a "systems approach," aspiring to simultaneously address multiple objectives and promote policy instruments and technological solutions that can be used across sectors.

In this section, we synthesize some of the most important strategies and policy recommendations distilled from the earlier sections of this chapter and from the "Roadmap to 2050: A Manual for Nations to Decarbonize by Mid-Century" (Carnevale and Sachs 2019) to which the authors of this chapter have actively contributed.[1]

There is a broad consensus on technology pathways to decarbonization which points to six main technological pillars: (1) **Zero-carbon electricity**: a shift toward zero-carbon electricity mix; (2) **Electrification of end uses**: the penetration of electricity, built on existing technologies, can enable a green conversion for the sectors currently using fossil-fuel energy; (3) **Green synthetic fuels**: deployment of a wide range of potential synthetic fuels, including hydrogen, synthetic methane, synthetic methanol, and synthetic liquid hydrocarbons applicable for harder to abate sectors; (4) **Smart power grids**: systems able to shift among multiple sources of power generation and various end uses to provide efficient, reliable, and low-cost systems operations, despite the variability of renewable energy; (5) **Materials efficiency**: improved material choices and material flows, such as reduce, reuse, and recycle to significantly improve materials efficiency; (6) **Sustainable land use**: mainly involving the agriculture sector, as it contributes up to a quarter of all greenhouse gas

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emissions from deforestation, industrial fertilizers, livestock, and direct and indirect fossil-fuel uses.

The present chapter has discussed the main technological decarbonization strategies available to decarbonize our energy systems for the power sector as well as the three final energy consumption sectors: industry, transport, and buildings. Here below, we present the main strategies and policy recommendations for each sector.

6.1 Strategies to Decarbonize the Power Sector

The power sector is already undergoing a decarbonization process in multiple countries around the world. The traditional centralized organization of the power system is now facing a paradigm shift to distributed and renewable generation. This new model is closely related tot he implementation of smart grids, where the end users act as prosumers. Digital technologies will be at the center of this revolution, unlocking the potential of different business models like virtual aggregators and peer-to-peer energy trading.

The current technologies supporting this transition can be classified into four main groups: (i) low-carbon energy sources (on- and offshore wind, solar PV and concentrated solar power, hydropower, biomass, nuclear, and geothermal); (ii) short-term and long-term electricity storage solutions; (iii) other flexible options such as network interconnections, sector coupling, supply response (hydro reservoirs, bioenergy) and demand-side management (DSM); (iv) carbon capture, utilization, and storage (CCUS), and variants including bioenergy CCUS and direct air capture. While many of these technologies are already cost-competitive and may offer even lower costs in the future, others (e.g., electricity storage and carbon capture) require future technological developments and/or increased economies of scale to support their effective deployment at the levels needed to reach a full decarbonization of the power sector.

The total decarbonization target will require a combination of multiple technologies. Depending on local conditions, the mix of available power options will vary from one country to another, and thus there will be no one-size-fits-all solution. The implementation of transition technologies may also be required. Coal should be phased out earliest given its high carbon content and its contributions to air pollution. While natural gas may play a crucial role during a transition period, it will also need to be either decarbonized or progressively phased out. To allow for unanticipated technological breakthroughs and cost reductions, energy policies need to be flexible, to be regularly assessed, and be adaptive to ongoing technology advances in order to allow each potential low-carbon solution to be supported and deployed.

While many national and international policies are heavily oriented toward the electrification of energy systems, electrification must proceed alongside decarbonization and uncoupling of energy demand from economic growth in order to fight climate change. Also, the energy efficiency potential along the whole electricity chain should not be underestimated. Moreover, a strongly integrated approach across sectors and energy pathways is essential for addressing climate change issues. Finally, secondary effects and a holistic perspective on the entire lifecycle of technological solutions should be considered to avoid potential rebound effects from specific technology choices.

6.2 Strategies to Decarbonize the Industry Sector

Heavy industry emits a large share of global greenhouse gas emissions, because industrial processes employ high temperatures and depend on high energy densities to enable the chemical processes involved. The industrial sector of the worldwide economy consumed more than half (55%) of all delivered energy in 2018. Within the industrial sector, the chemicals industry is one of the largest energy users, accounting for 12% of global industrial energy use.

Three energy-intensive sectors have been considered: cement, iron and steel, and petrochemicals (plastics, solvents, industrial chemicals). Fully decarbonizing such complicated and integrated industrial environments requires a multidimensional approach. Strategies include (i) reducing demand for carbon-intensive products and services; (ii) improving energy efficiency in current production processes; (iii) deploying decarbonization technologies across all industries, which in turn can be split between four supply-side decarbonization routes: electrification, use of biomass, use of hydrogen and synthetic fuels, and use of carbon capture technology.

Some material efficiency options for the three industry sectors analyzed include (i) for cement: building design optimization, concrete reuse, materials substitution; (ii) for iron and steel: optimization of scrap recycling, product design for efficiency, more intensive use of products; (iii) for petrochemicals: chemical and mechanical recycling, plastic demand behavior change, use of renewable feedstocks, and product eco-design to better enable recycling. For these industries, improvements in energy efficiency should run in parallel with material efficiency and demand reduction.

Appropriate technology for energy efficiency exists today and it can be applied in any country. Some of the key solutions for energy efficiency improvement include (i) for cement: switch to dry kilns, multistage cyclone heaters; (ii) for iron and steel: reuse of high-pressure gas for power, coke dry quenching; (iii) for petrochemicals: energy efficiency in monomer production and naphtha catalytic cracking.

There are currently no pure technological limitations blocking major decarbonization routes across any industrial sector. The barriers are economic and not technological; we have the technologies today but they are expensive.

Of course, also geographical contexts will impact technology decision-making. Countries investing in new plants should go for zero-carbon technology rather than investing in energy efficiency improvements in plants at the end of their life. In contrast, countries where legacy plants and facilities will continue to operate for years to come should invest in energy conservation and energy efficiency improvements for existing processes. Additionally, the possibility of combining more of these solutions in a given country or facility will vary and depend on the geographical distribution of resources and social acceptability of specific technologies.

6.3 Strategies to Decarbonize the Transport Sector

The transport sector requires deploying a diverse mix of decarbonization solutions to meet the challenges within each of its four main segments: roadways, railways, aviation, and navigation. Effective decarbonization pathways in transport rely mostly on technological solutions, new sustainable fuel development and fuel shifts, and are complemented by demand reduction and modal shift strategies.

Direct electricity usage (through either batteries or electrified railways and electric road systems), hydrogen, synthetic fuels, and sustainable biofuels (properly allocated to hard-to-decarbonized modes) will all be important for transport decarbonization. Strategies include (i) in the road segment, CO_2 emissions are easier to abate due to electric vehicles and fuel-cell electric vehicles for short-to-medium haul (freight, passenger, light-duty, or heavy-duty categories); (ii) the pathways for railway decarbonization are mostly based on fuel shifts from diesel to electricity or hydrogen; (iii) in aviation, advanced jet fuels (such as synthetic fuels) are the only way to decarbonize the current fleet and the relevant one in the near future. Modal shift from air to land could be enhanced with innovative alternatives such as ultra-high-speed trains with the right policies in place; (iv) long-haul navigation is hard to abate while short-haul navigation can be supplied by electricity or hydrogen technologies. Ammonia and hydrogen are currently being investigated in long-haul navigation.

The use of biofuels and the sustainability of biomass for biofuels need to be carefully assessed so as to avoid: competition with food production, deforestation or loss of biodiversity in natural regions, and competition with industries that currently use the biomass for higher value products or uses. As sustainable biofuels will only be available in limited volumes, its use should be prioritized in hard-to-abate modes like aviation.

Regulatory frameworks need to be technology agnostic to create a fertile environment for innovation, unleashing the potential of the research while fostering virtuous behaviors of citizens in all transport modes.

6.4 Strategies to Decarbonize the Buildings Sector

Buildings represent an estimated 36% of global final energy consumption and 39% of the global energy-related greenhouse gas (GHG) emissions. The goal of total decarbonization in the buildings sector includes the construction of new buildings and districts with zero or almost zero energy consumption from fossil fuels and the total renovation of existing buildings with the same net zero-carbon standards. Current renovation rates account for about 1% of existing building stock each year, while to achieve 100% zero-carbon goal by 2050 it is necessary to ensure a renovation rate higher than 3%. It should be noted that the CO_2 emissions resulting from material use in buildings represent almost one-third of building-related emissions: the construction industry must radically change its manufacturing structure in order to abate this increasing embodied energy.

In general, using a combination of readily available technologies and approaches, and performance-based design metrics, net zero-carbon buildings and districts can be achieved today by (i) maximizing the buildings energy efficiency mainly through passive and low embodied carbon solutions; (ii) adopting high-efficiency technical systems and advanced control/management strategies: phasing out inefficient solutions, encouraging of low-carbon systems such as heat pumps and district heating and the adoption of advanced control/management strategies; (iii) maximizing on-site or nearby renewable energy production and self-consumption while electrifying the buildings sector, to completely cover or exceed the total energy demand of each building with the minimum exchange of energy with the grid (thus stimulating energy management, storage, and exchange at district level).

In order to achieve the overall decarbonization of the buildings sector, energy consumption related to building codes be addressed. The strategies include (i) establishing advanced building energy codes with mandatory performance standards and setting minimum energy performance levels for existing buildings. Also, policies and subsidies to favor the retrofit of existing buildings rather than new constructions are absolutely necessary; (ii) achieving high-efficiency building envelopes at negative life cycle cost, mandating energy performance standards for envelope components and work with industry to deliver non-invasive and whole-building retrofit packages. Policy-makers should develop strategic frameworks to create the adequate market conditions for low-carbon technologies, guiding building owners and designers in making the correct choices; (iii) mandating minimum energy performance standards for stand-alone heating equipment, prevent expansion of fossil-fuel heating, and pursue strategy to shift demand to high-efficiency and integrated energy solutions with net zero emissions; (iv) pursuing low-cost solar cooling technologies such as high-efficiency and renewable district cooling where appropriate. Mandating the use of waste heat from large-scale cooling for heating and hot water use on-site or via district systems, local governments are uniquely positioned to advance district energy systems in their various capacities; (v) implementing regulations and measures obstructing energy self-consumption such as specific additional taxes or levies should be lifted and administrative procedures to allow self-consumption should be user-friendly; (vi) achieving affordable thermal storage and low-cost solar thermal systems (for low-income countries only); (vii) implementing training and capacity building activities for the construction sector must be adequately promoted, while also pushing the development of specific DSS (decision support system) or design-aid tools to strongly increase the application of climate-responsive and integrated building design.

6.5 An Integrated Systems Perspective Needed

Due to the complexity of the decarbonization process across the whole energy system, it is important to adopt an integrated system approach. A systems perspective recognizes the interconnectivity of actions toward any one or more of these objectives, using any one or more of the mentioned policy instruments or technological solutions. An action in one can be detrimental to another, while some combined efforts could amplify their cumulative effects and achieve multiple objectives. For example, the power grid itself represents a complex system that must continue to operate reliably and efficiently even as it undertakes the deepest transformation in its history. No single policy or technology can achieve decarbonization by itself or be implemented without due consideration to its ripple effects, or to the delicate state of the current, broader system.

In taking a systems approach, many complementarities need to be considered for managing the complexity of the energy system: (i) complementarities of variable renewable energy sources. Wind, solar, and hydropower vary by the minute, day, season, and year. Digital systems will play a large role in coordinating the augmented grid complexity and the required flexibility; (ii) complementarities among zero-carbon technologies. As one obvious example, zero-emission vehicles depend on complementary zero-carbon energy sources and the infrastructure to fuel them; (iii) complementarities of public and private investments. Parts of the energy system are in private, for-profit hands, and parts are publicly owned. It will take significant effort and analysis to harmonize public and private investments, to recognize the diverse role they can play, and the synergies their joint action can create; (iv) complementarities of natural and engineered systems. Achieving net negative emissions would require biological storage of carbon dioxide (CO_2) in vegetation and soils via preservation of existing forests, restoration of degraded habitats, and reforestation to increase natural carbon sinks. Energy strategies that amplify land use degradation must be ruled out; (v) complementarities of mitigation and adaptation. Adaptation measures can also contribute to mitigation strategies. Forest restoration and protection of coastal wetlands would help resist storm surges from rising sea levels, promote resilient food production, and secure carbon, thereby serving both adaptation and mitigation purposes; (vi) complementarities of centralized and decentralized solutions. Renewable energy resources are by nature different from one place to another and restriction on land availability and use may require different power configurations; (vii) complementarities of actions and strategies in different geographies. Efforts to address decarbonization might be similar for big cities in North America and in Europe, but they would not apply to sub-Saharan Africa. Urban areas are also different from rural areas where the fight to bring access to energy and other services to all is still a challenge. Trying to impose the same pathway in different contexts can lead to failure and to the continuation of business-as-usual scenarios; (viii) complementarities of R&D activities supported by research institutions and academia, funded by public and private sectors. These activities should aim at promoting breakthrough innovation to feed continuously the process of decarbonization and keep under control any risk of lock-into solutions that may fail to contribute to total decarbonization in the long run.

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