Chapter 6: Energy Systems

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Executive Summary

The global energy system will need to produce net-zero CO_2 around 2050 to 2065 to limit warming to 1.5°C, and several decades after to limit warming to 2°C. The Paris goals cannot be met without largely eliminating energy system CO_2 emissions. Reaching net-zero CO_2 emissions by 2050 would require CO_2 emissions to decrease by about 2.2% to 3.3% per year for the next 30 years, as compared to average growth of over 2% per year from 2000 to 2018. (*medium confidence*) {6.7}

In contrast, energy demands and emissions have continued to rise. Fossil fuel CO_2 emissions from the global energy system grew at an average annual rate of 1.26% between 2010 and 2019 reaching a historic high of 38 $GtCO_2$ yr^{-1}, despite declining energy intensity in almost all regions. (*high confidence*) {6.3}

Costs have dropped rapidly over the last five years for several key energy system mitigation options, particularly solar PV and battery storage. Investment costs for PV dropped 80% from 2010-2020. Battery costs dropped by ⅔ between 2015 and 2020. These cost reductions have spurred adoption and have catalysed changes in electricity generation and in the transportation sector. Low-carbon electricity is now cheaper than fossil generation in many regions, electric vehicles are increasingly competitive with internal combustion engines, and large-sale battery storage on electricity grids is increasingly viable. (*high confidence*) {6.3, 6.4}

Installed wind and solar PV capacity has increased substantially in recent years. Combined they constituted 9% of global electricity generation in 2020 and are poised for large-scale deployment over the coming decade (*high confidence*). Policy, societal pressure to limit fossil generation, low interest rates, and cost reductions have all driven wind and solar deployment (*high confidence*). From 2013 to 2018, low-carbon electricity generation increased by 23%. The vast majority of the growth was solar PV and wind power, which grew by 215% and 75%. Growth of other low-carbon electricity sources has been limited. Low-carbon electricity generation technologies currently produce less than 40% of global electricity. (*high confidence*) Low-carbon electricity will need to produce almost 100% of global electricity by 2050 to limit warming to for either 1.5°C or 2°C. (*medium confidence*) {6.3}

If current investment trends continue, not only will emissions increase, but the energy system will be "locked-in" into higher emissions, making transformation even harder. Many aspects of the energy system are resistant to change or take many years to change. Physical infrastructure like electric power plants, pipelines, or buildings can last for decades. Institutions, laws, and regulations can take decades to evolve and can hold back the rapid changes needed in the energy system. Societal adjustments to new technologies can take years as well. Continued investments in emitting or inefficient infrastructure, particularly investments in coal-fired electricity, will substantially increase the challenge of meeting the Paris goals. The combined economic impacts of stranded fossil fuel resources and capital could amount to trillions of dollars. (*high confidence*) {6.7}

Future low-carbon power systems will be increasingly weather-dependent, amplifying possible climate change impacts locally and nationally and potentially influencing national mitigation strategies. Climate change may have both positive and negative implications on energy supplies. There is substantial uncertainty about these implications, but it is likely that climate change will have an important influence on some local and national energy systems, altering hydropower potential, bioenergy and agricultural yields, thermal power plant efficiencies, and demands for heating and cooling. Climate change could also increase the vulnerability of power systems through heat waves, limits on cooling water, seasonal disruptions in renewable power generation, and direct impacts on power system infrastructure. (*high confidence*) {6.5}

The most strategic approach to carbon-neutral energy systems will vary by region, but these systems will share several common characteristics. This includes: electricity systems that produce zero CO_2 or that remove CO_2 from the atmosphere; widespread electrification of end uses, particularly in areas such as light-duty transport, space heating, and cooking; substantially lower use of fossil fuels than today, targeted use of alternative fuels (e.g., hydrogen, bioenergy, ammonia) to substitute for fossil fuels in harder to decarbonise sectors; more efficient use of energy than today; greater integration across regions and components of the energy system; and use of some level of carbon-dioxide removal (e.g., direct air capture or bioenergy with carbon dioxide capture, utilisation or storage (CCUS)). (*high confidence*) {6.6}

Electricity systems powered predominantly by renewables will be increasingly viable over the coming decades, but it will be challenging supply the entire energy system entirely with renewables (*high confidence*). Research increasingly indicates that large shares of variable solar PV and wind power can be incorporated in electricity grids through batteries, other forms of storage, broader transmission systems, advanced controls, and greater demand side responses (*high confidence*). Economic, regulatory, and operational challenges increase with higher shares, and the ability to overcome these is not fully understood (*high confidence*). Beyond electricity, hard-to-decarbonise sectors, such as aviation, industry, and agriculture, will make 100% renewable energy systems more difficult to attain (*medium confidence*). {6.6}

A number of energy supply options are competitive today to support near-term mitigation, while others await continued improvements, to be viable for large-scale deployment. Solar PV and wind power are already cheaper than fossil electricity in many locations and are becoming competitive in others. Nuclear power is economically viable in some circumstances, but public and political support, along with improved construction management and reactor designs to lower costs, will be important to allow its broader use. Biofuels hold the promise of broadly supplanting fossil fuels in some applications, but next generation conversion processes are not yet cost-effective, and a broad set of challenges associated with bioenergy crop production remain. CCUS is technologically ready, but remains in the demonstration stage and will always cost more than comparable processes in which CO_2 is not captured and stored, necessitating strong policy support. Hydroelectric power continues to be a major source of electricity, but the potential for increased deployment is modest when considering broader environmental constraints. (*medium confidence*) {6.4}

While action needs to be taken across all sectors of the economy, some energy sector mitigation options can provide more immediate emissions reductions than others. Key near term actions include deploying low- and zero-carbon electricity sources; halting the construction of new coal-fired power plants and retiring existing coal-fired power plants; limiting the construction of new gas-fired power plants; installing electric heaters ("heat pumps") in homes and businesses; replacing cars using gasoline with those using electricity; and installing more efficient technologies wherever possible. These should be accompanied by efforts to improve and test out options that will be important later on, including fossil power plants or bioenergy power plants or refineries with CCUS, hydrogen produced from water electrolysis using carbon-free electricity, synthetic fuels, and carbon-neutral ammonia. (*medium confidence*) {6.4, 6.7}

The viable speed and scope of energy system change will depend on how well such change can support broader societal objectives. While many studies have identified "cost-effective" energy systems, countries will make choices on how to navigate an energy system transition based on a wide variety of factors. Energy systems are linked to air and water pollution, energy security, food security, economic prosperity and international competitiveness, employment, and provision of the basic energy-related services (such as heating, cooling, lighting, cooking). Energy system transformation will not occur if it strongly conflicts with these goals. {6.7}

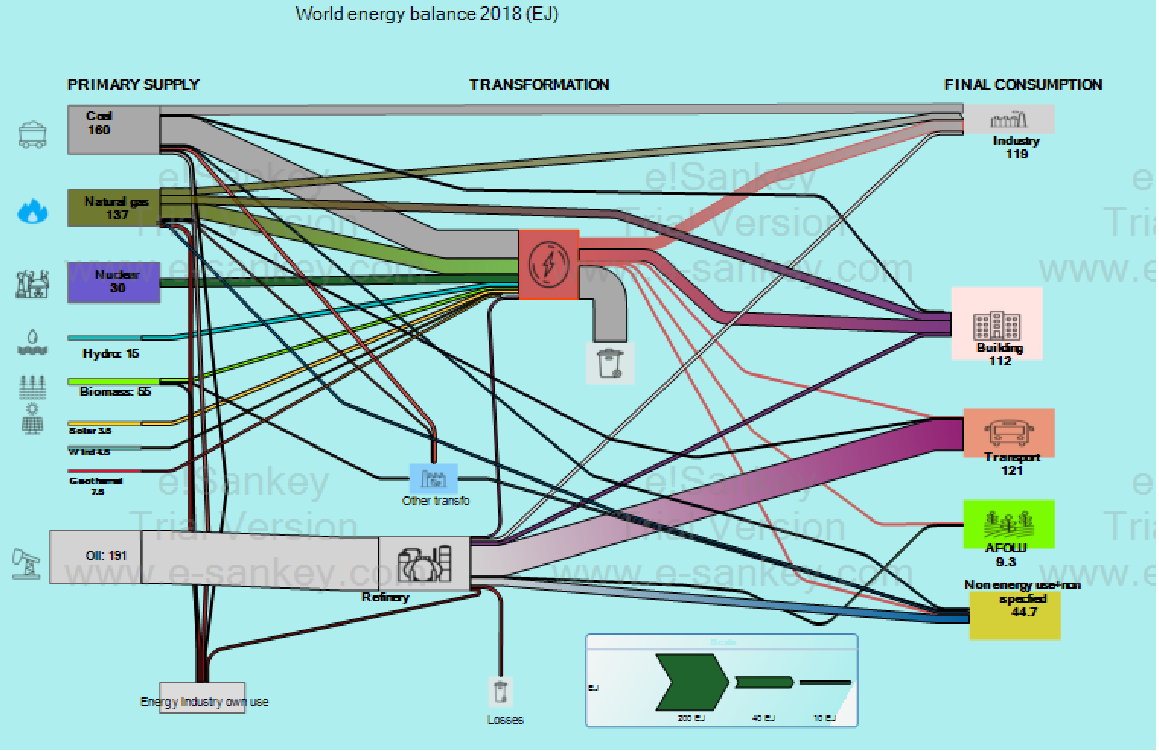
Energy system mitigation will create stranded assets associated with fossil resources and infrastructure, reduce the value of these assets, and eventually dramatically reduce the size of fossil-related industries. The combined economic impacts of stranded fossil fuel resources and capital could amount to trillions of dollars. New investments in fossil generation, particularly coal generation, without CCUS are inconsistent with limiting warming to 1.5°C. While natural gas generation provides near-term reductions relative to coal-fired generation, it creates emissions and will need to be retired early in many countries if energy-sector emissions are to be brought to zero. Investments in petroleum refining may be stranded with a move to electric transportation infrastructure. Most fundamentally, limiting warming to 1.5°C or 2°C will decrease the use and value of fossil fuels. This will affect those industries, individuals, and societies that depend on fossil revenues and fossil-related jobs, raising the importance of policies to ensure just transitions. *(high confidence)* {6.7}

Energy system transformation will require a shift in investment patters and create a range of new economic opportunities associated with low-carbon energy systems. Emerging industries, such as renewable energy industries or non-fossil transportation are set to grow substantially. (*High confidence*) Limiting warming to 1.5 °C will require a rapid expansion of investment in energy supply, from the current USD 1.8 trillion per year, to USD 2 -3 trillion per year in 2030, to USD 2.5 -4 trillion per year in 2050. If warming is limited to 2°C, investment in energy supply will gradually increase, reaching USD 1.5 -2.5 trillion per year in 2030 and USD 2.5 -3.5 trillion per year in 2050. (*Medium confidence*) {6.7}

Cost reductions in key technologies have driven down expectations for near-term mitigation costs. Near-term costs are heavily dependent on the costs of reducing emissions from electricity and increasing electrification, and they may well be negative or zero in some circumstances. Long-term mitigation costs are not well understood and depend on policy design and implementation, future costs and availability of technologies in hard-to-decarbonise sectors (e.g., process heat, long-distance transport) and the development of electrification processes in end-use sectors. Long-term costs are likely to be moderate in many circumstances. Major advances in low-carbon energy resources and carriers such as second-generation biofuels and hydrogen would substantially improve the economic attractiveness of net-zero energy systems. (*Medium confidence*) {6.4, 6.7}

6.1 Introduction

The global energy system is the largest source of CO_2 emissions (Chapter 2). Reducing energy sector emissions is therefore essential to limit warming. The energy systems of the future will be very different than those of today if the world is successful in limiting warming to well below 2°C or to 1.5 C. Energy will be provided in different ways, converted in different ways, and used in different ways (Figure 6.1). Achieving and responding to these changes presents an impressive range of challenges and opportunities.



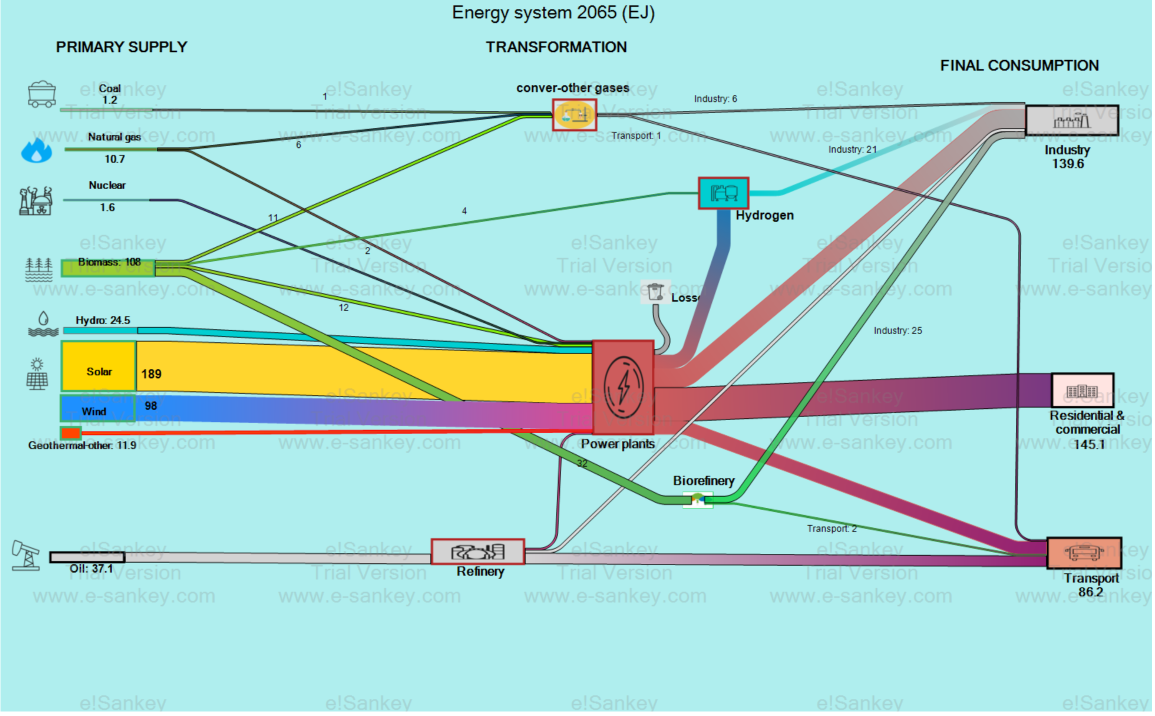


Figure 6.1 Energy flows within the current energy system (top panel) and within an illustrative future, net-zero CO_2 emissions energy system (bottom panel).

Source: IEA, IPCC Database. *[Note to reviewers – these figures are still under development, due to different accounting practices between historical data and future scenarios. Notably, future scenarios should still include energy for AFOLU and non-energy applications. This will be addressed in the final version of the figure.]*

Within this context, this chapter has two main objectives. First, it assesses specific, individual mitigation options in energy supply, transformation, and transportation and transmission. This second focus is complementary to a set of chapters that explore mitigation options in agriculture, forestry, and other land uses (Chapter 7), urban systems and other settlements (Chapter 8), buildings (Chapter 9), transport (Chapter 10), industry (Chapter 11), and cross-sectoral perspectives (Chapter 12). Second, this chapter aims to assess system-level mitigation opportunities and challenges across the entirety of energy systems. This system includes energy supply, transformation, transmission, storage, and transportation, and end uses and end users. It also includes the societal systems that interact with the physical energy system. As energy systems become increasingly integrated and interconnected, a system-wide perspective is necessary for understanding mitigation opportunities and challenges.

Within this context, this chapter addresses six questions, each of which is addressed in a separate section. First, as a matter of setting the stage, what is the scope of the energy systems and potential change (Section 6.2)? Second, which recent trends in energy systems might exert the greatest influence on energy system evolution and options for reducing emissions (Section 6.3)? Third, what is the status and potential of individual energy supply, transformation, storage, transportation and transmission, and integration options (Section 6.4)? Fourth, how might climate change affect energy systems and alter potential energy system mitigation options and strategies (Section 6.5)? Fifth, what are the key characteristics of "net-zero" energy systems – those that emit no CO_2 or that actually sequester CO_2 from the atmosphere (Section 6.6)? Sixth, and finally, what are the transition pathways toward and through net-zero energy systems (Section 6.7)?

6.2 The Scope of the Energy System and its Possible Evolution

For the purposes of this chapter, energy systems are defined broadly to include both physical and societal elements. The physical infrastructure includes all the infrastructure and equipment used to extract, transform, transport and transmit, and convert energy to provide energy services. In addition to the physical system, a broad range of societal systems and dynamics are relevant to the energy system. Human societies use energy to transport themselves and the goods that they use and consume, to heat, cool, and light their homes, to cook their food, to travel, to produce goods and services. Energy systems are therefore tied to the systems involved in the provision of these various goods and services. All energy users engage in the operation of energy systems by demanding energy at particular times and in particular forms. They can adjust their behaviour and demands, for example, by using less energy or by adjusting when they use energy. Consumers can make investments in equipment that reduces their energy needs, and they can invest in energy transformation (e.g., rooftop solar) and storage. Firms and governments invest in equipment to produce, transform, and transport energy, from power plants to oil tankers. All aspects of energy systems are governed by laws, regulations, and actual institutions that reside within businesses and governments at all levels, for example, rules for trading emissions permits, deciding when particular electricity generation technologies might come on line, water management and related environmental rules that define the availability of hydropower or influence water availability for cooling power plants, regulations for injecting CO_2 into underground reservoirs or disposing of nuclear waste, and even company policies regarding work hours or teleworking, which can have important implications for energy demand profiles. Many people are employed in the energy sector, and energy system mitigation will reduce eliminate some jobs while creating others.

This broader view of energy systems is essential for understanding energy system mitigation, as these broader societal and institutional factors can have an important influence on energy system transformations and the potential to rapidly reduce energy CO_2 emissions. Energy system mitigation is as much about the challenges of societal change as it is about the challenges of changes in energy in physical infrastructure, technologies, and operations. While this chapter does not attempt to draw a specific boundary around all the different systems that interact with the energy system, it frequently explores these broader system interactions when assessing different mitigation options and strategies.

There is no single spatial scale at which energy systems might be defined and assessed. They can be assessed at the scales of homes, cities, states or provinces, countries, regions, or the entire world. These different scales are frequently both distinct with their own internal dynamics yet also connected to one another. This chapter most frequently assess energy systems from the country and global perspective.

6.3 Recent Energy System Trends and Developments

6.3.1 Energy sector emissions continue to grow, although the rate of increase continues to decline

[Note: The energy supply system is defined in this section as encompassing all primary energy, conversion, and transmission processes with the exception of those that use final energy to provide energy services in the end-use sectors (transport, buildings, industry and agriculture). The full energy system includes energy end uses sectors.]

Current energy sector emissions trends, if continued, will not limit global temperature change to “well below 2°C” (IPCC 2018). Global energy system fossil fuel CO_2 emissions grew at an average compounded annual rate of 1.3% yr^{-1} between 2010 and 2019 reaching a high of 38 $GtCO_2$ yr^{-1}, and accounting for approximately two-thirds of annual global anthropogenic emissions (Figure 6.2).

Coal was the single largest contributor to emissions between 2010 and 2018, accounting for about 45 % of emissions. Oil accounted for about 35% of emissions, and natural gas accounted for about 20%. Coal, oil and natural gas CO_2 emissions grew respectively at annual rates of 0.37% yr^{-1}, 0.44% yr^{-1} and 0.89% yr^{-1}. The power industry remains the single largest source of energy sector GHG emissions, accounting for about 38% in 2018, followed by industry at 22% and transport (excluding international shipping and aviation transport) at about 18% (Figure 6.3 top right). Shipping and aviation international accounted for less than 3.3%. These relative proportions have remained relatively unchanged over the last decade. These trends reinforce the near-term challenges facing energy sector mitigation – power sector emissions continue to rise despite rapid deployment of wind and solar power (6.3.5); transportation emissions continue to rise, and petroleum remains the dominant fuel, despite advances in batteries and electric cars (6.3.7). Some specific sectors, such as shipping and aviation may present longer-term challenges.

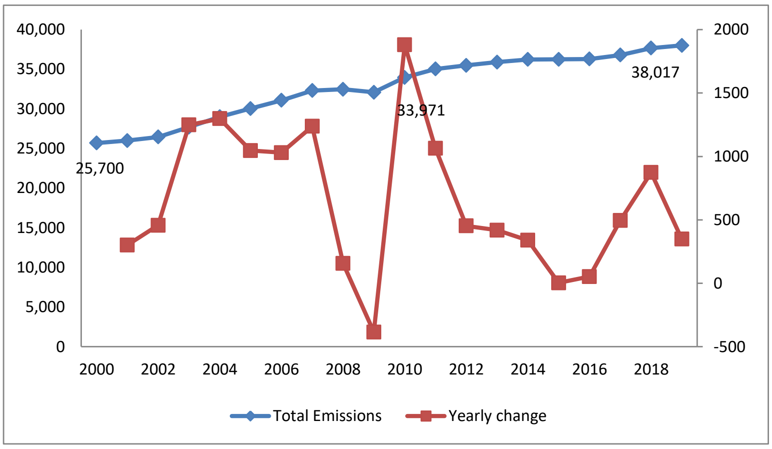
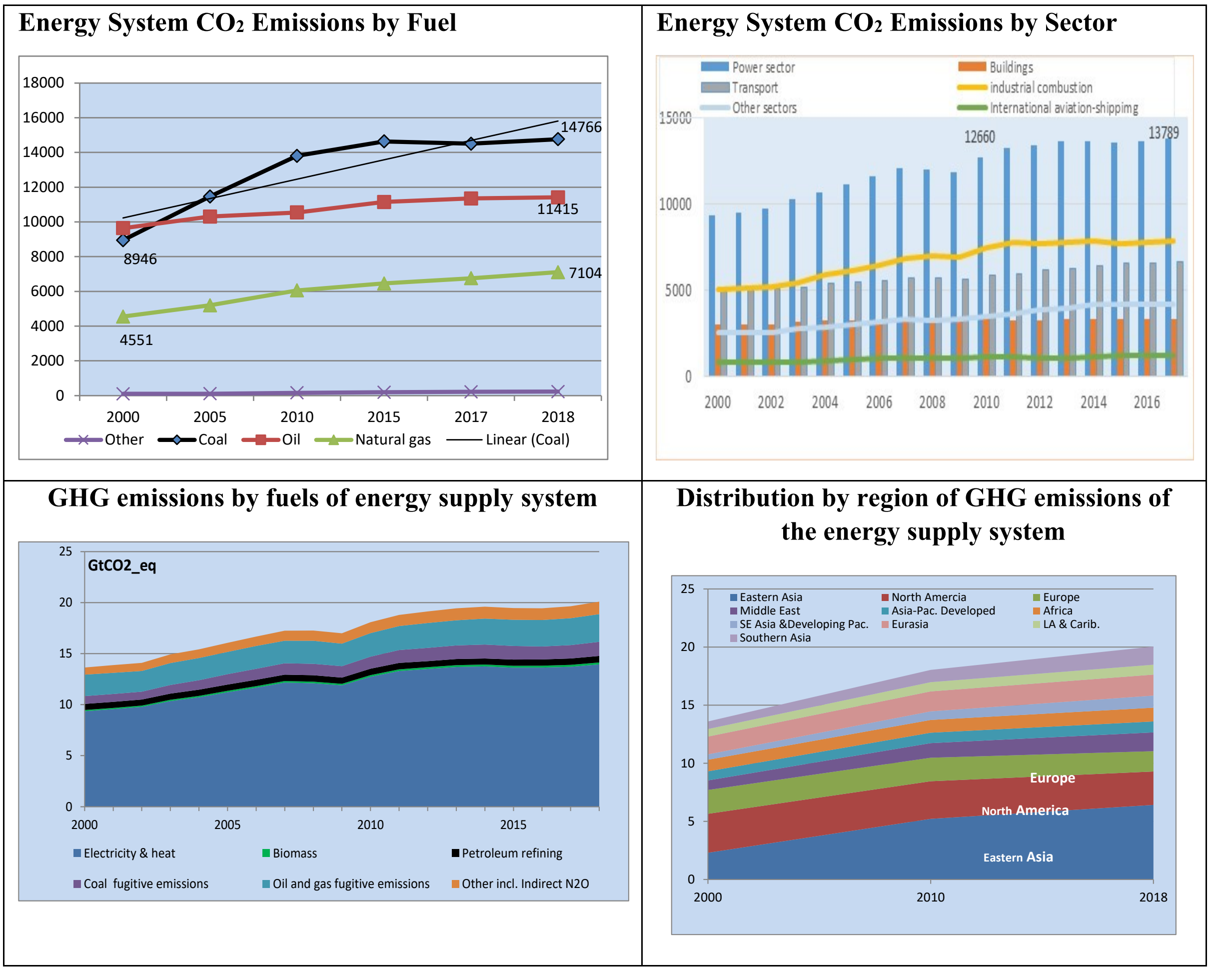


Figure 6.2 Global fossil fuel CO$_2$ emissions and annual change 2000-2019* (MtCO$_2$).
(Source: adapted from Crippa et al. 2020.)

Energy supply GHG emissions reached 20 GtCO$_2$-eq in 2018, rising from 18 GtCO$_2$-eq in 2010. Approximately 20% of energy supply emissions were non-CO$_2$ emissions, particularly methane as fugitive emissions in oil, gas, and coal operations. Energy supply GHG emissions grew at an annual rate of 1.33% yr^{-1} between 2010 and 2018. They were roughly flat between 2013 and 2016, then rose by1.6% yr^{-1} from 2016 to 2018. Electricity and heat contributed approximately 70% of total energy supply GHG emissions in 2018 (Figure 6.3 bottom left). This growth has occurred despite the high penetration of solar PV and wind utility-scale power plants particularly in Asia and developed countries.



Energy System CO$_2$ Emissions by Fuel

Energy System CO$_2$ Emissions by Sector

GHG emissions by fuels of energy supply system

Distribution by region of GHG emissions of the energy supply system

Figure 6.3 Top left Global energy-related CO_2 emissions by fuel ($MtCO_2$ yr^{-1}), and Global Energy GHG emissions by sector ($GtCO_2$-eq yr^{-1})1990-2018

(Source: IEA fig 62 top right and bottom (Crippa et al. EDGAR database)

Despite the declining energy intensity, global energy system CO_2 emissions have closely tracked GDP per capita. This is especially the case in the Asian economies, which have experienced rapid GDP per capita growth in the past decades and a massive rise in energy demand (Liao and Cao 2013; Zhu et al. 2014). Similarly, emissions have declined in times of economic downturns – for example, in Eurasia in the 1990s and globally in 2009. Population growth is also a contributing factor globally and in most regions particularly Africa, albeit to a significantly lower extent than economic growth. Energy intensity has decreased across all regions since 2010, with a global average of -2.1% yr^{-1}, which has helped to hold in check the implications of economic and population growth. However, there is no region where this factor alone would have been sufficient to decrease CO_2 emissions from the energy system. In Europe and North America, the only two regions where emissions decreased meaningfully since 2010, a steady decrease in the carbon intensity of energy was the other significant downward driver. In the case of the EU, the reduction in carbon intensity is largely due to the increase of renewable electricity production coupled with the low levels of fossil fuel-based production in the energy mix (Dyrstad et al. 2019).

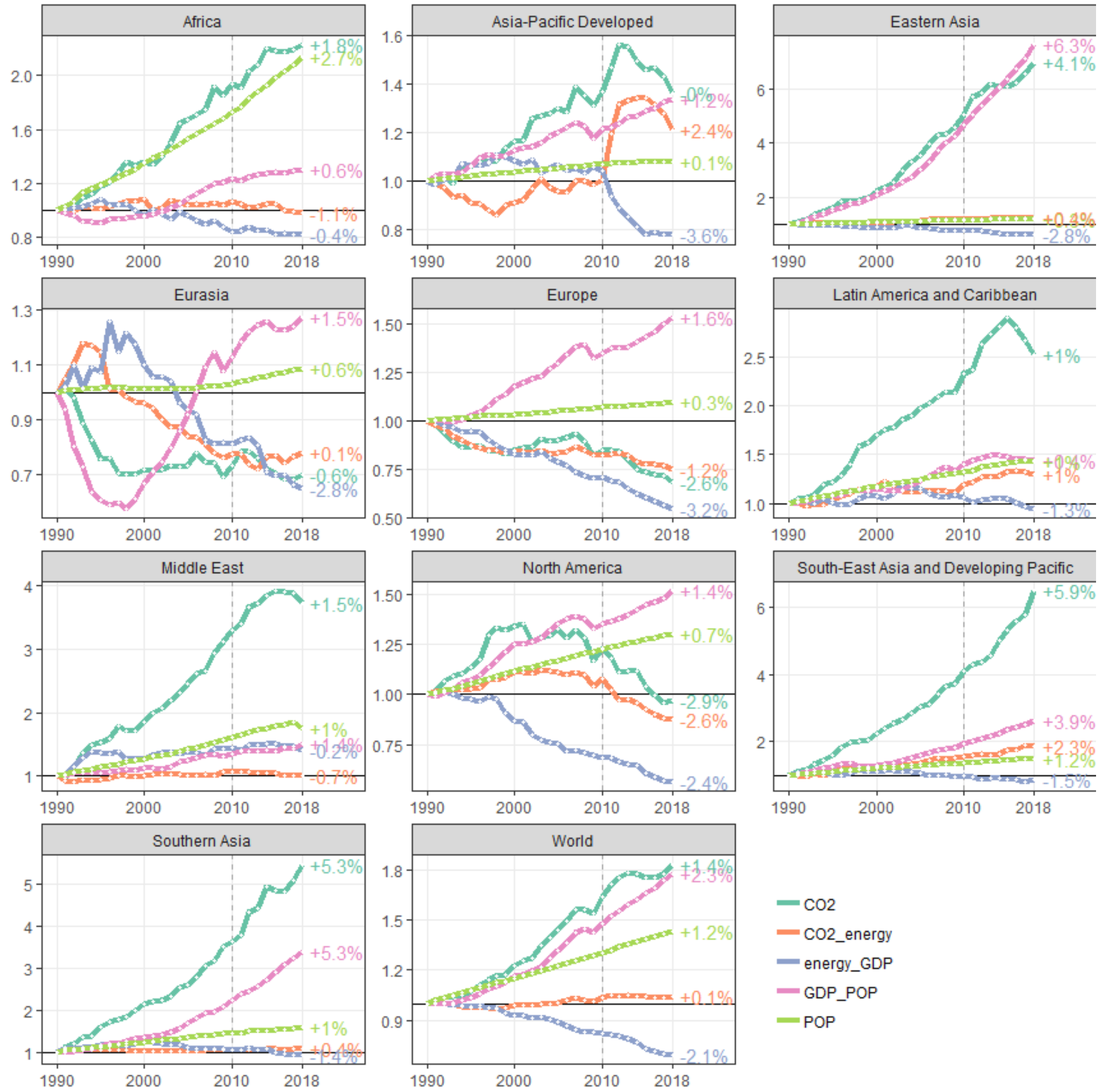


Figure 6.4. Drivers of greenhouse gas emissions across selected regions

Fugitive emissions from fossil fuel production, primarily methane, accounted for about 20% of sector supply emissions in 2018, with 2.7 Gt CO_2eq yr^{-1} linked to oil and gas production and 1.2 Gt CO_2eq yr^{-1} to coal mining (EDGAR data (Crippa et al. 2019)). Oil and gas operations produced 2.9 GtCO_2eq yr^{-1} in 2019 (82 Mt yr^{-1} as methane), split roughly equally between the two (www.iea.org/reports/methane-tracker-2020/methane-from-oil-gas). There remains a high degree of uncertainty in methane emissions estimates from oil and gas operations despite the emergence of new data from satellites and other measurement campaigns. According to a recent study (Hmiel et al. 2020), methane emissions are underestimated by about 25 to 40 per cent.

The marginal increase in petroleum and refining emissions since 2010 can be explained by the refining capacity and the demand for petroleum products. During the decade 2008-2018, the annual growth rate of the refining throughput was only 1% and remained unchanged between 2018-2019 (BP, 2020). Biomass emissions are mainly from biomass power plants and charcoal manufacturing. These emissions remain low, at less than 1% of the energy supply system GHG emissions. It is nevertheless important to highlight uncertainties regarding emissions from biomass particularly for charcoal manufacturing given the informality of the charcoal value chain.

Increasing energy system CO_2 emissions has been driven by rising emissions in China, India, and other emerging economies; however, per capita CO_2 emissions in these countries still remain well below developed countries. From 2015 to 2019, East Asia, South Asia, and South-East Asia energy sector CO_2 emissions grew at annual rate of 6.0% yr^{-1}, 5.6% yr^{-1}, and 4.4% yr^{-1}. The relative shares of Europe and the U.S. have continue to decline, in part because of declining emissions in Europe, and in larger part due to the growth in other countries (Figure 6.4 and Figure 6.3 bottom right).

6.3.2 Global energy production and demand continue to grow, although the rate of increase continues to decline

Recent changes in the energy system can be viewed within the context of longer-term trends in energy supply and use. Over the last decade, there has been a significant increase in the total primary energy supply (TPES) and some structural changes in energy sources. TPES grew 1.4% yr^{-1} from 2010 to 2018, from 540 EJ to 602 EJ. Natural gas consumption grew most quickly during this period, at 2.2% yr^{-1}. Coal and oil grew at annual rates of 0.64% yr^{-1} and 1.2% yr^{-1}, respectively. In 2018, the share of coal, oil and natural gas in the TPES was respectively 28%, 32% and 21%, representing only a modest shift from 2010, when the shares were 27%, 32% and 23%. Renewables, excluding hydropower, grew at annual rate of 11.5% during this period however their share remains marginal in 2018 with just 2% of the TPES as compared to 0.9% in 2010 (Figure 6.5 left).

The total final energy consumption (TFC) increased 1.5% yr^{-1} from 2010-2018, rising from 369 EJ to 414 EJ. This is a much lower growth rate than in the previous decade (2.8 % yr^{-1}) (Figure 6.5 right). In 2018, oil and particularly oil products used for transportation accounted for 41% of the TFC. This trend reflects that the penetration of non-fossil fuels is still marginal despite a significant growth of electric vehicles during the recent years. Coal still accounted for 10% of the TFC in 2018, dropping only marginally from 12% in 2010. Coal is mainly used as a primary source of energy in industry and to a lesser extent in the residential sector. The share of electricity increased modestly, from17% in 2010 to 19% in 2018, reflecting increasing access in developing countries and increasing use of electricity for a wide variety of end uses in the residential sector (see Box 6.1). Heat accounts for approximately 3% of the TFC and is mainly used in industry and the residential sector. Biofuels and waste accounted for 11% of the total final consumption in 2018, only modestly changed from a decade earlier.

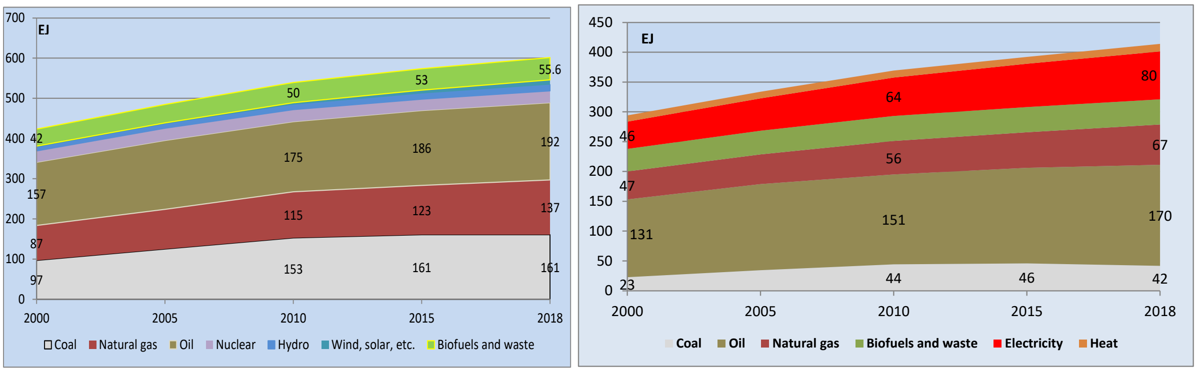


Figure 6.5 World Total Primary Energy Supply (TPES) (EJ) and total final energy consumption (TFC) 2000-2018 (adapted from IEA world energy balances (database for IPCC)

There are important differences in fuel use across countries. While developed countries almost exclusively use modern fuels, many countries still obtain a large fraction of their energy from traditional biomass. Traditional biofuels (fuelwood and charcoal) are particularly important in the TFC of sub-

Saharan countries and some Asian countries such as India particularly in the residential sector for cooking. Africa is still characterised by a high share of traditional biomass (mainly fuelwood) in the primary supply and final consumption. In 2018, biomass and waste in Africa accounted for more than 80% of the TPES against 9.2% on average worldwide.

Asia has been particularly important in TFC growth since 2000. In 2018, Non OECD-Asia and China accounted for more than a third of the TFC (IEA 2020a). In contrast, TFC has remained stable in the OECD over the last decade. Despite a steady increase, Africa's TFC remains relatively low (6.2 % of the world TFC) particularly in sub-Saharan countries. Approximately 860 million people mostly in sub-Saharan Africa and some Asian countries lacked access to electricity and about 2.65 billion to clean-cooking facilities in 2018 (IEA, 2019). Achieving universal energy access (SDG-7) will require energy transitions in the domestic sector, including new developments in off-grid energy technologies, emphasis on rationalising energy subsidies, and increasing efforts to address health concerns related to the use of traditional fuels.

6.3.3 Non-climate factors continue to drive energy systems changes

While climate change is important in driving energy system changes, recent energy system changes have arisen in response to a much broader set of factors beyond climate change mitigation, including energy access, energy security, air pollution, and technological progress in key mitigation technologies.

Energy Access. Between 2000 and 2016, nearly 1.2 billion people gained access to electricity. Increasingly, those who gain access are doing so via renewable sources, and decentralised systems are proving cost-effective way in rural areas (IEA 2017). Between 2000 and 2016, the number of people in developing countries with access to clean cooking has grown by 60%, and the number of people cooking with coal and kerosene has more than halved (IEA 2017). (See Box 6.1)

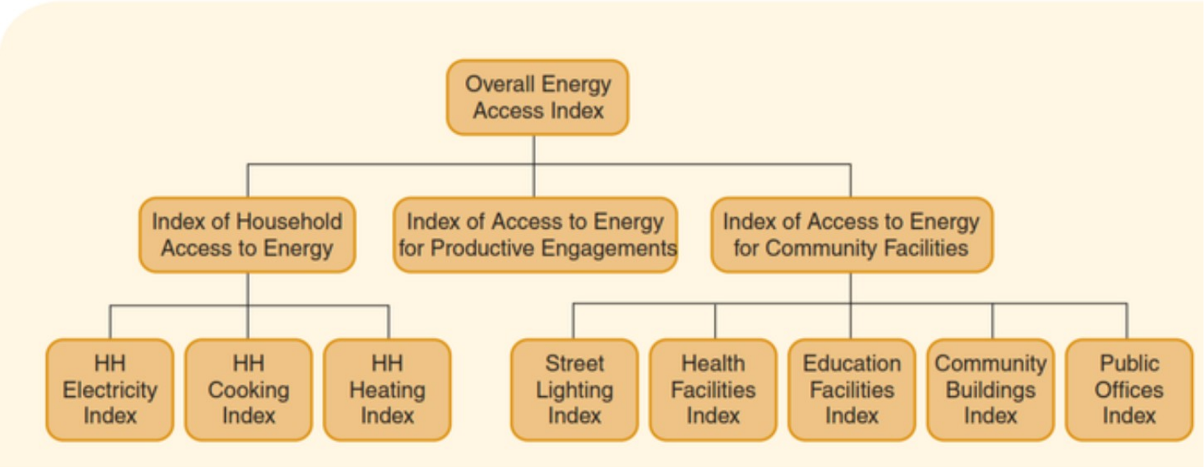
Energy Security. For decades, energy security debates largely overlooked climate concerns. Energy security was often constructed as national security and therefore prioritised above climate concerns (Nyman 2018). Progressively the role of sustainability and environmental degradation to human security became evident (Cool 2011), and climate change and improving energy security began to be addressed as two of the twenty-first century's greatest challenges (Brown Marilyn A. & Benjamin K. Sova Cool 2011). More recently, the relationship between climate change and energy security has been systematically investigated (Toke and Vezirgiannidou 2013).

Air Pollution. In China, the capital region established a target of a 25% PM2.5 concentration and released a policy that included the shutdown of all coal-fired power plants and their replacement by gas power plants in Beijing and an increase in the share of imported electricity through the extra-high-voltage transmission connection (Fang et al. 2019).

Technology. The falling costs of solar PV, wind, and batteries is driving a major change in the way that electricity is produced and potentially in personal transportation (Section 6.3.5, 6.3.6). Technological changes and climate interact with one another and reinforce one another. Recent advances in PV, for example, can be traced in part to aggressive deployment policies spurred by environmental concerns; and decreasing costs are creating markets for PV even without climate policy or are easing the ability to implement climate policy. In Germany, the transition strategy of *Energiewende* is under debate because of its over cost, an element that could change the direction for renewable energy in that country (Leslie et al. 2016) In China, there was a decline in new additions of wind and PV capacity between 2018 and 2019. The winding-down of renewable energy feed-in tariffs (FITs) is the main factor. This change in the Chinese policy is an attempt to address growing deficits in the funds used to pay for the subsidies (Hove 2020).

Box 6.1 Energy access, energy systems, and sustainability

Successful mitigation must operate in tandem with fundamental development goals such as modern energy access. In many developing countries, access to electricity, clean cooking fuels as well as modern and efficient energy for income generation remains an essential societal priority. This is particularly true in sub-Saharan Africa and a few Asian countries. SDG7 on universal access to modern energy includes targets on modern energy services, renewable energy, and energy efficiency, which implies a profound transformation of the current energy systems. Although there are different definitions of energy access, the ultimate goal is universal access to clean and modern fuels.



Box 6.1, Figure 1 Measuring access to energy (Global tracking framework)

Despite progress in some countries such as India, Bangladesh and Kenya, 860 million people were without access to electricity in 2018, compared with 1.2 billion in 2010. About 2.65 billion households were cooking with solid fuels, distributed across both Asia and Africa (IEA, IRENA, UNSD, World Bank 2020).Around 850 million people in sub-Saharan Africa relied on traditional biomass (firewood and charcoal) for cooking, and 60 million relied on kerosene and coal to meet their energy needs (IEA 2018a). It has been estimated that 2.2 billion people will still be dependent on inefficient and polluting energy sources for cooking by 2030 mainly in Asia and Sub-Saharan Africa, and 650 million people are likely to remain without access to electricity in 2030, 90% of whom will reside in Sub-Saharan Africa (IEA, IRENA, UNSD, World Bank 2020).

Research indicates that decentralised renewables and on grid renewables are least cost options to provide universal access to electricity by 2030; natural gas, LPG, and improved biomass cookstoves are key measures for cooking. Universal access to electricity and clean cooking requires the rapid shift from the use of traditional biomass to cleaner fuels and/or clean cooking technologies (IEA, IRENA, UNSD, World Bank 2020). Riahi et al. (2012) finds that this is feasible over the next 20 years and will require USD 36 billion yr^{-1} to USD 41 billion yr^{-1} in annual investment, half in Africa.

Substantial progress towards SDG, even without reaching universal access by 2030, will have an important impact on energy systems, particularly power systems with the deployment of renewable energy, natural gas infrastructure, LPG, and biomass supply chains (*high confidence*). Providing universal energy access will substantially increase global energy demands (*high confidence*). Chakravarty & Tavoni (2013) calculated that eradicating energy poverty at the global level by 2030 would mean increasing final energy demand by 7%, and that the necessary infrastructure would generate around 44-183 $GtCO_2$ during the century, increasing warming by approximately 0.13 ° C. (Nussbaumer et al. 2012) found that power generation in sub-Saharan Africa would need to increase ten times to provide even modest levels of universal energy access, implying growth of 13% yr^{-1} compared to 1.7% yr^{-1} in previous decades.

6.3.4 Initial efforts to phase out coal but only modest declines in use

Global coal consumption declined from its peak in 2013 through 2016, increased from 2017 to 2018, and dropped again in 2019 (Figure 6.5). A number of important themes emerge regarding recent trends in coal consumption. First, coal is faring differently across regions. Coal use is decreasing in the U.S, the European Union, and many other OECD countries. Many of these regions have implemented moratoriums on new coal power generation without (CCUS) (Jewell et al. 2019). In contrast, coal use continues to increase in other regions, especially in major developing Asian economies (IEA 2020b). Coal-fired power generation capacity growth in China, India, and other countries, such as Indonesia, Vietnam, Turkey, and Bangladesh, has offset the reduction in the OECD (Jakob et al. 2020).

Second, reductions in coal use have often been driven by non-climate factors, most notably environmental regulations to address air pollution, rapidly declining costs of renewables, and inexpensive shale gas especially in the U.S. Older coal fired power stations that cannot meet new environmental regulations or have become unprofitable or uncompetitive have been phased out in many regions. For example, air quality concerns in China have led to a shutdown of coal fired industry and power generation around the major cities, while overcapacity and low and declining utilisation of coal plants have slowed down new builds since 2016 (Cui et al. 2019).

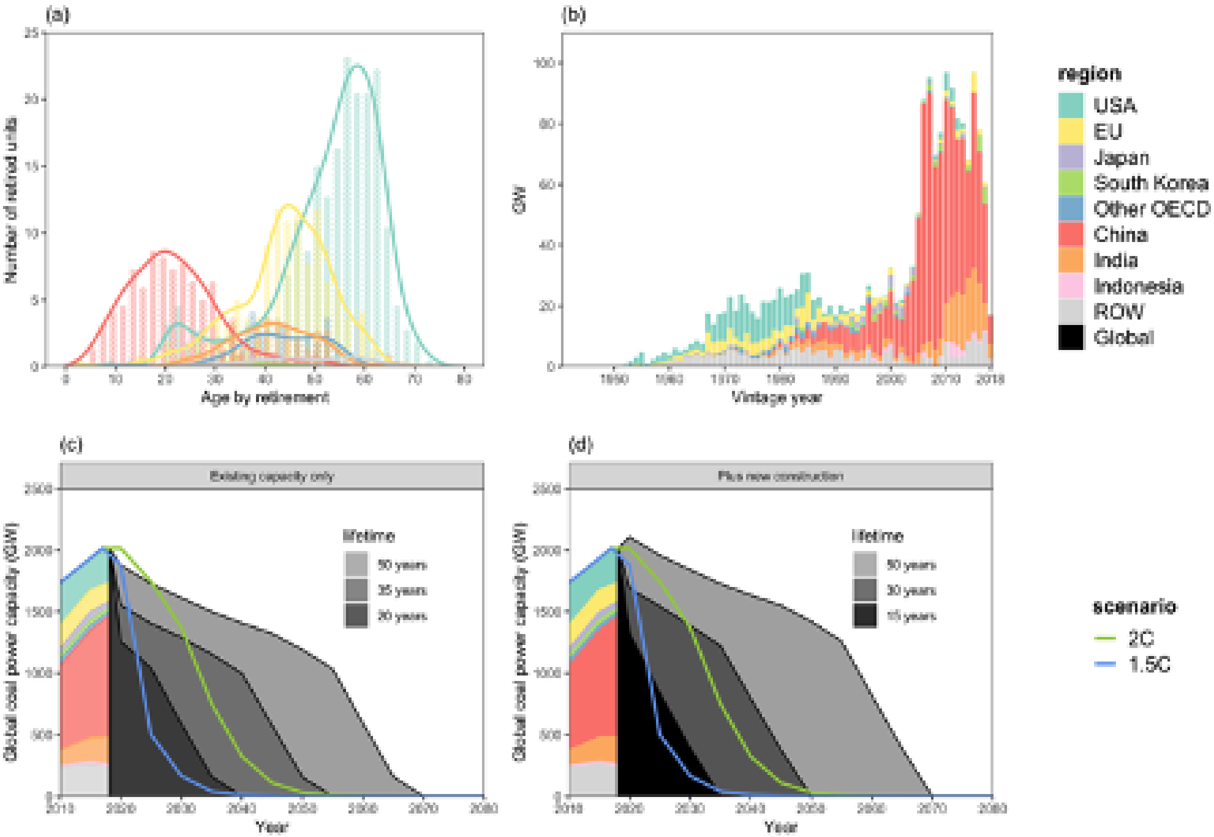
Third, retired coal has been replaced by different energy sources across regions. Old coal fleets have been replaced approximately half by gas and half by renewables in the U.S., largely by renewables in the European Union, and by new coal plants and renewables in China (EMBER 2020). Although air quality concerns have pushed out the old, dirty, inefficient coal plants in China, larger and more efficient coal plants are being added. Replacing coal with gas or new coal facilities is inconsistent with limiting warming to 1.5ºC or 2ºC (Pfeiffer et al. 2016; Pfeiffer et al. 2018; Smith et al. 2019; Tong et al. 2019).

Fourth, major coal consuming countries are still far from phasing out coal (Spencer et al. 2018; (Edenhofer et al. 2018). China, the U.S., Australia and South Africa continue to extract and use substantial amounts of coal. In most developing countries with abundant coal reserves, coal use has been increasing to support energy security and because it is perceived to have lower costs than alternatives (Steckel et al. 2015). Many challenges confront a coal phaseout, including the depreciation of capital costs of existing coal plants, a failure to internalise the externalities of coal use, and a failure to properly account for the increasing business risks of coal (Garg et al. 2017b). Continued coal builds will increase the risks of stranded assets in developing countries (see Box 6.11) (Farfan Orozco 2017; Saygin et al. 2019; Cui et al. 2019).

Last, economic, social, and employment impacts tend to be significant in coal-dependent regions. Tailored reemployment has been used to support coal transitions in some regions. Although some estimates show larger employment opportunities from low-carbon energy (Garrett-Peltier 2017), results may vary across regions. Moreover, even with net increase in total employment in the long run, renewable jobs are often located outside of coal regions and require different skill sets from the coal industry (Spencer et al. 2018). In a broader sense, a "just transition" has to include the impacts on regional economic development and the effects of higher energy prices for consumers and energy-intensive industries (see Box 6.2) (Jakob et al. 2020; Green and Gambhir 2020).

Box 6.2 Status and Challenges of a Coal Phase-Out

Limiting global warming to well below 2ºC or to 1.5ºC requires a rapid shift away from unabated coal consumption in the energy system by 2050 (IPCC 2018a Section 6.7, Chapter 3). This includes not only cancellation of new coal power projects but also accelerated retirement of existing coal plants (Kriegler et al. 2018; Pfeiffer et al. 2018; Smith et al. 2019). Without new builds, existing coal plants will need to be retired after 20 years of operation to limit warming to 1.5ºC goal and after 35 years to limit warming to 2ºC. If all planned facilities come online, this will further reduce the viable lifetime of all plants by 5 to 10 year (Cui et al. 2019). Phasing-out coal will present a number of different economic, social, and security challenges, and these will vary across regions based on the characteristics of existing coal infrastructure, the availability of alternatives, economic development, and technological and institutional lock-in, a (Jakob et al. 2020). The following examples help to identify the mechanisms driving the move away from coal – whether market-driven, policy cap or societal benefits. They also enable a better forecasting for the anticipated volatilities in the oil and gas sector, where a phase-out is not immediate but imminent but will be needed to limit warming to 1.5°C or 2°C (IPCC 2018; Raimi et al. 2019).



Box 6.2, Figure 1 Retirement of coal-fired power plants to limit warming to 1.5°C and 2°C. (a) Historical facility age at retirement (b) the vintage year of existing units, (c) global coal capacity under different plant lifetimes, compared to capacity levels consistent with a well-below 2°C (green) and 1.5°C (blue) pathway assuming no new coal plants, and (d) and assuming plants currently under construction come online as scheduled, but those in planning or permitting stages are not built.
(Source: Cui et al. 2019).

Today, several countries and regions have committed to or operationalised coal phase-out (Watts et al. 2019; Jewell et al. 2019). These initial efforts have not reached the 5-7% in global annual reduction required to limit warming to 1.5°C target, and most have occurred in regions with older coal fleets, these initial efforts provide insight into the possible mechanisms of global and regional strategies (Spencer et al. 2018). Current coal phase-out examples are often driven by profitable fuel switching (to gas or renewables), strong policy choices, internalising externalities to increase the price of coal, or other considerations such as air quality and human health, and electricity access. Many financial institutions and pension funds have committed not to fund new coal or coal-based infrastructures, and have assumed a carbon price in the range of USD 35-45/tonne CO_2 for assessing new investment proposals (Nie et al. 2016; World Bank et al. 2017).

Europe: A number of European countries are part of the Powering Past Coal Alliance (PPCA) and have committed to phase-out coal on or before 2030 (Jewell et al. 2019). These countries have a cumulative capacity of only 43 GW, however, and are economically-developed and thus can more easily opt for alternative energy routes. Moreover, premature retirement is rare for achieving these goals due to aging coal plants in these countries (Jewell et al. 2019). Germany and Poland, with around 70 GW of operating coal capacity, are not members of the PPCA, but are critical for phasing out coal (Whitley et al. 2017). While Poland has not set any target, the German government adopted an official plan in 2019 to phase out coal no later than 2038 and possibly by 2035 based on economic circumstances. The German government agreed in early 2020 on a set of measures that include compensation for power plant closures, labour market measures for coal workers, and substantial support of structural change in coal-mining regions. The experience of European efforts to phase out coal indicate that appropriate financial instruments are needed (Rentier et al. 2019) and a just transition for workers should be ensured (Johnstone and Hielscher 2017; Osička et al. 2020).

North America: Coal is also being phased-out in North America. In the U.S., this has occurred with limited policy support. Instead, the availability of cheap shale gas that has reduced coal use by over 50% in the U.S. from 2008 (EIA 2019). Canada, as one of the two founding countries of the PPCA, has committed to phase out traditional coal power generation by 2030 (Government of Canada 2018). This commitment, combined with cheap renewables or environmental regulations in particular regions, shows that even with inclusion of CCUS, coal use is projected to decline (Mendelevitch et al. 2019; Clark 2019; Rosenbloom 2018, 2019). Broadly, this phase-out of coal has resulted in multiple benefits, with noted decreases in GHG emissions, air pollutants, and cooling water use (Harris et al. 2015) (Kondash et al. 2019). However, there have been concerns about the fate of coal workers. For instance, in the U.S., coal-related employment has decreased by about 30,000 jobs with notable regional and economic inequities (Bodenhamer 2016; Abraham 2017; Greenberg 2018). If sustainably managed, there may be possibilities for reemployment or even additional employment by diversification, say through bioenergy with carbon capture and storage (BECCS) (Patrizio et al. 2018; Homagain et al. 2015).

China and India: China and India are the largest coal consumers and have no committed plans to phase out coal. A phase-out here will provide several health benefits, particularly in terms of air pollution (Peng et al. 2018; Dholakia et al. 2013; Singh and Rao 2015; Malik et al. 2020). China announced a coal moratorium in 2015, which was also predicated on cutting overcapacity (Blondeel and Van de Graaf 2018). The coal power expansion has slowed since then, but coal capacity has been growing, and there have been recent increases in new coal approvals (Cui et al. 2020). In India, over 50% of proposed new coal plant capacity has been cancelled since 2016 (Monitor Global Energy. 2019), and rural electrification efforts and a push to support renewables may lead to preferential investments in solar and wind (Aklin et al. 2017; Thapar et al. 2018). India has retired about 8.5 GW of inefficient and old coal based plants between 2016 and 2019 (CEA 2019). Both China and India have demonstrated an approach to shut down coal plants in similarly densely populated centres such as Beijing and Delhi (Gass et al. 2016). Chinese and Indian coal plants are newer than those in the U.S. and E.U., which are already approaching the end of their operational lifetime, and would thus would face a larger risk of stranded assets under accelerated retirement (Cui et al. 2019).

Africa: Announced coal projects in Africa have increased. While the planned capacity in countries other than South Africa is low, competing narratives between sustainability and energy security have been noted (Jacob 2017). In South Africa, employment in the coal mining sector has almost halved since 1980’s and is projected to fall down to 22,000-42,000 by 2050, as compared to the current levels of 77,000 (Strambo et al. 2019; Cock 2019). Given income inequality in South Africa, a sustainable transition for these workers is essential through reemployment in the growing renewable sector will be critical (Swilling et al. 2016).

6.3.5 Solar PV and wind deployment has grown substantially but shares in global electricity generation remains low

Since 2015, global solar PV and wind capacities have continued their rapid growth (28% and 12% respectively). However, their corresponding contributions to total electricity generated from all sources were below 4% in 2018. In the past fifteen years, the levelised cost of electricity from solar PV and wind have dropped dramatically and deployment levels have increased around the world (Section 6.4). After the initial deployment in Europe and the U.S., more than 90 countries now have commercial wind energy plants. Total global cumulative capacity was 622 GW in 2019), 95% of which came from onshore wind. Asia has the highest installed capacity, led by China but the growth has slowed down post-2015. PV and wind deployment in Europe, initially a leader in these technologies, has been surpassed by rapid growth in Asia, led by China, India and Japan. Europe's share in total global cumulative photovoltaic capacity decreased to 24% in 2019 due to rising installations elsewhere (IRENA 2020a). Recent growth in Asia has more than compensated for the decrease in new capacity additions in Europe. CSP deployment has also continued to grow, but it remains far below PV. Production remains in a limited number of countries with high Direct Normal Irradiance (DNI). About 75% of total installed capacity is in Spain and the US.

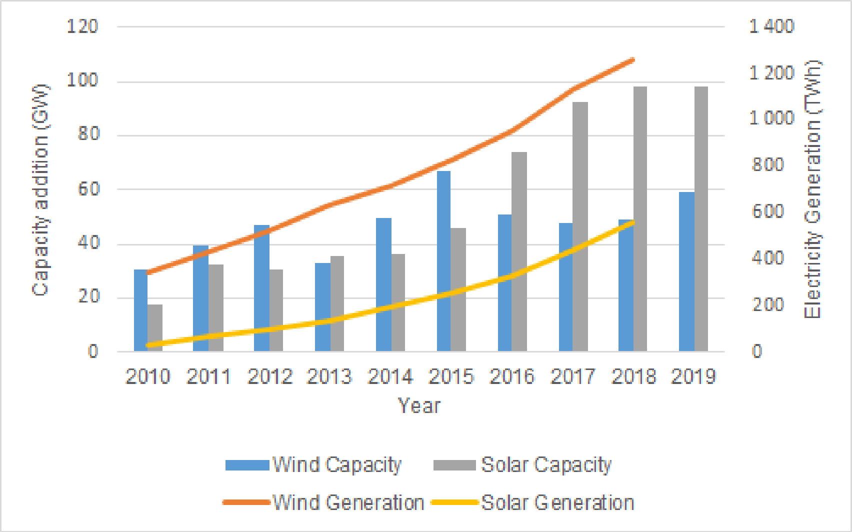


Figure 6.6 Yearly addition (MW yr^{-1}) to global solar and wind capacity from 2010-2019 along with their respective electricity generation (GWh) between 2010-2018.

Source: data from (IRENA 2020a).

While the deployment of wind and PV remain low in total relative to generation from other sources, the recent growth rates signal the potential to achieve the contributions required to limit warming to 1.5°C or 2°C (see Section 6.7.1). The critical question will be whether these growth rates can be maintained at the necessary levels, or whether concerns with retiring fossil power (Section 6.3.4) or challenges with integration of renewables (Section 6.6) will slow or limit this growth.

6.3.6 Limited deployment of low- to negative-carbon energy resources beyond solar PV and wind

Apart from solar PV and wind, low- and negative-carbon energy fuels and technologies such as hydropower, modern bioenergy, geothermal, marine, and carbon capture and storage (CCS) experienced limited deployment over the last decade (Lovins et al. 2018). Global hydropower production grew 2% since 2015, and its share of total electricity generation has remained at 16% (IEA WEO 2019); IEA Statistics(2020)[1]). Advanced bioenergy applications such as power generation, liquid biofuels and biogas have experienced modest increased in deployment (IEA 2019; IRENA 2020b). Global bioenergy power generation went up from 460 TWh yr^{-1} to 590 TWh yr^{-1} from 2015 to 2019, an annual growth rate of 7%; biofuels production for transportation from 3140 PJ yr^{-1} to 4020 PJ yr^{-1}, an annual growth rate of 6% (IEA 2019a). Global nuclear power capacity has increased from 380 GWe to 400 GWe and its share of global electricity production, has continued its long decline, from a 17% share in 1996 to about 10% in 2019. Carbon capture and storage (CCS) remains largely in the research and demonstration phase without a meaningful impact on global CO_2 emissions and no immediate prospects for large-scale deployment. Global CCS capacity was around 40 $MtCO_2$ yr^{-1} in 2019, with 19 large-scale operational projects (Global CCS Institute 2019). There are now a number of ongoing and upcoming CCS projects (51 in 2019) with a capacity of 40 $MtCO_2$ yr^{-1} from operation and in-construction plants. Further, the plants under early and advanced stages of development in 2019 could provide additional capacity of around 60 $MtCO_2$ yr^{-1} (Global CCS Institute 2019). Geothermal energy output in 2018 was estimated at 175 terawatt-hours (TWh), with around half of this in the form of electricity and other half as heat (REN21 2019; IRENA 2020a; IRENA 2020b). Geothermal for electricity generation is concentrated in a limited number of countries and the prospects for large scale development in the next decade are relatively limited, based on the current scenario (IRENA 2020a; IRENA 2020b). The share of marine energy in the electricity mix has doubled since 2010 but remains too little (1 TWh in 2018) to make any substantial impact towards low-carbon energy transitions (IRENA 2020a; IRENA 2020b) (See section 6.4.2.9).

6.3.7 Battery electricity storage has advanced rapidly

Recent years have seen rapid declines in the costs of energy storage, particularly batteries (see Section 6.4). These changes have had important implications for the energy systems, most notably in supporting increased deployment of intermittent renewable generation and electrification of the vehicle fleet.

Battery electricity storage has emerged as an important element in flexibility of electricity systems to accommodate the rising share of intermittent renewable energy. Total power sector battery capacity at the grid and consumer end reached 10 GW in 2019, rising from 0.6 GW in 2015. In 2018, the total battery storage deployment was 8 GW (17 GWh), led primarily by Li-ion technologies (IEA WEO 2019). Nonetheless, energy storage continues to be dominated by pumped-storage plants which account for 96% of all electricity storage. The installation cost of battery storage has fallen down by over 45% since 2012 (Section 6.4). As of 2018, the largest Li-ion battery storage was 100 MW (127 MWh) in Australia followed by 50 MW (300 MWh) in Japan. Future project announcements include comprehensive renewable-plus-solar projects like the 400 MW (800 MWh) solar plus storage project in California to replace retiring gas plants (Roy et al. 2020)) or the solar-plus-storage tenders for round the clock electricity supply in India (Burke and Do, 2020). These large scale energy storage projects in many countries have further pulled down the cost of battery storage. At the same time, fire hazards and other technology related concerns have slowed down the deployment of utility-scale batteries in Korea which is a leading player in energy storage (IEA 2020c) (See section 6.4.3).

FOOTNOTE [1] https://doi.org/10.1787/data-00510-en

EV battery capacity reached 170 GWh per year in 2019, raising the demand for low cost battery technologies. EV battery capacity has grown over 40% in the last 5 years. A total of 7.2 million electric cars accounted for 1% of global car stock in 2019 along with 7.3 million charging stations across the world (IEA 2020d). Average battery size increased to 50-70 kWh. The rising battery size is the result of an increasing range of EVs and consumer preference for full-battery electric vehicles (BEVs) over plug-in hybrids (PHEVs). The cost of battery packs has also decreased to USD 56/kWh in 2019, a drop of 85% since 2010 (see Section 6.4). As in case of utility-storage, the battery packs in EVs are currently dominated by Li-ion technology with further improvements in efficiency and range expected in the next decade or so (IEA Global EV Outlook, 2020) (see Transport Chapter).

6.3.8 The energy policy landscape continues to evolve

The current policy landscape in the energy sector consists of policy mixes or policy packages, including regulatory, market-based and other approaches. These mixes evolved over time rather than being constructed in a consistent manner and mainly include sectoral rather than economy-wide policy instruments, such as comprehensive carbon pricing.

Governments, national and sub-national, have chosen a mix of policies and institutional mechanisms that consists of regulatory instruments, like efficiency and technology standards, economic instruments (e.g. carbon pricing, subsidies) (Bertram et al. 2015; Martin and Saikawa 2017) as well as other policies, such as government interventions to provide appropriate infrastructure, information policies, and voluntary actions by citizens, businesses and other non-government actors (Somanathan et al. 2014). In recent years, regulatory instruments to promote low-carbon infrastructure have gained traction in developing countries (Finon 2019). The choice of policies has depended on institutional capacities, technological maturity and other developmental priorities of governments. For example, governments may favor regulatory instruments over economic instruments like taxes and subsidies when there is sufficient institutional capacity to implement and monitor the regulations and standards (Hughes and Urpelainen 2015) . Furthermore, institutional capacity could also determine the extent of implemented measures (Adenle et al. 2017). Market conditions and technological maturity are other important determinants of policy mixes. For example, subsidies for mitigation like feed-in-tariffs (FIT) work best when the technologies are in nascent stages of development and their effect may start declining as the technologies mature (Gupta et al. 2019a). On the other hand, for more mature technologies, market-based instruments like emission trading schemes (ETS) and auctions coupled with a regulatory framework could be a favorable strategy (Polzin et al. 2015; Kitzing et al. 2018). Policy instruments like FIT followed by fiscal measures like tax incentives and renewable portfolio standards (RPS), have played a significant role in attracting foreign direct investments in the renewable energy sector (Wall et al. 2019). Furthermore, FIT has been an important policy instrument in driving the penetration of wind and solar energy but aggregate policy support and carbon pricing have also played an important role in mainstreaming of these renewable energy sources (Best and Burke 2018). Besides high effectiveness, FIT may have substantial program costs (Andor and Voss 2016; Abrell et al. 2019).

The role of carbon pricing is still limited though increasing. Carbon taxes and emissions trading schemes (ETS) were considered as key policy instruments to address climate change in a cost-effective manner (Haites 2018; Baranzini et al. 2017). Different measures have been suggested to improve the performance of the ETS and other carbon pricing schemes (Bataille et al. 2018; Campiglio 2016; (Goulder and Morgenstern 2018). In 2020, 61 regional, national and sub-national carbon pricing instruments, representing 22% of the global GHG emissions, were in action or scheduled for implementation (World Bank 2019a). Over 51% of emissions covered are priced at less than USD 10 per tonne of CO_2 equivalents (tCO_2-e). Most studies indicate that carbon prices need to be substantially higher than this in order to meet the Paris goals through pricing instruments (Stiglitz and Stern 2017). At present, however, only 5% of the global emissions covered under carbon pricing initiatives are consistent with this suggested range of carbon prices. The impact of carbon pricing is sizable even though its full potential is not exploited, e.g. the EU ETS impacts on emissions from electricity in Germany (Schäfer 2019) and from manufacturing in France (Colmer et al. 2020).

The limited success of carbon pricing instruments in developing and emerging economies may be due to political economy constraints (Campiglio 2016; Finon 2019; Rabe 2018). In the absence of a global comprehensive carbon price, it has been suggested that regional regulatory policies for fossil fuels supply and key demand sectors like transport, industry and buildings, coupled with regional carbon pricing instruments, can help in initiating the climate actions consistent with Paris agreement, at least in the short run (Kriegler et al. 2018). However, differences in the stringency of climate regulation can reduce the competitiveness of industries in regulated countries and might lead to industry re-location and "carbon leakage" (Schenker et al. 2018). There is currently little indication of carbon leakage (Schäfer 2019; Naegele and Zaklan 2019; for the EU ETS) and there might be even positive effects of carbon pricing on efficiency (Löschel et al. 2019), for German manufacturing firms, and Germeshausen (2020) for German power plants). Furthermore, these multiple policies - often implemented by different governmental levels (national vs. subnational) - can interact with each other and thereby affect their environmental and economic effectiveness. Recent examples include interactions of ETS with renewable support policies (e.g. Boehringer and Behrens 2015; Del Rio 2017) energy efficiency policies (e.g. Wiese et al. 2018) or electricity market reform (e.g. Teng et al. 2017), respectively.

Apart from explicit carbon pricing, various implicit carbon pricing mechanisms such as fossil fuel taxes and removal of fossil fuel subsidies (see Box 6.3) as well as regulatory instruments are used by many countries as part of their climate policies. In addition, public provision and procurement of low-carbon infrastructure and technologies such as railways, energy efficient devices, renewable energy and upgradation of electricity grids through state-sponsored institutions and public-private partnerships has played an important role in low-carbon development (Baron 2016).

Box 6.3 Energy Subsidies

Energy subsidies continue to be widely applied. Global fossil fuel subsidies represent more than half of total energy subsidies with predominantly negative environmental, economic and social effects (*high confidence*).

Energy subsidies can be defined as policy measures in the energy sector to lower the prices for consumers, raise the prices for producers or lower the costs of energy production (IEA 1999). There are subsidies for fossil fuels and renewables. The majority of the renewable subsidies are generation-based incentives for solar, wind or biomass in the form of feed-in-tariffs (FIT) (see Chapter 13 for more details on subsidies for mitigation). Estimates of fossil fuel subsidies can vary by an order of magnitude. For the year 2017, the IEA estimated fossil fuel subsidies of USD 300 billion using IEA's pre-tax, price-gap method (Laurens 2017), while the IMF included unpriced externalities to calculate subsidies of USD 5.2 trillion or 6.5% of global GDP (World Bank 2019b)(World Bank 2019, Coady et al. 2017, Coady et al. 2019, see Chapter 13 for more details). Fossil fuel subsidies were around double the amount of subsidies spent on renewables (Laurens 2017). There are adverse environmental, economic and social consequences of fossil fuel subsidies (Rentschler and Bazilian 2017). More than 75% of the distortions created by fuel subsidies are domestic and reforming them can have substantial benefits within the country (Coady et al. 2017, 2019). Some of the G-20 countries have used the opportunity of low oil prices to implement subsidy reforms (Jewell et al. 2018). Fossil fuel subsidies most commonly pursue non-climate objectives, for example enhanced access to modern energy sources, such as liquefied petroleum gas for cooking (*high confidence*). In some cases, these energy access subsidies have helped in extending modern energy sources to the poor (e.g. Kimemia and Annegarn 2016) and thereby contribute to SDG-7. However, in most cases, the subsidies have proven to be regressive with little benefit reaching the poor (Lockwood 2015; Sovacool 2017).

For example, Indonesia has introduced liquefied petroleum gas (LPG) subsidies for cooking. These subsidies shall reduce expenditures on kerosene subsidies after surging oil prices made these subsidies increasingly costly. The kerosene to LPG conversion program ("Zero Kero") was launched in 2007 and provided mainly households with free initial LPG equipment and LPG at a low subsidised price (Thoday et al. 2018; Imelda et al. 2018). Besides the national government, provincial governments and industry played a crucial role for implementation. Provincial governments decided on licenses for LPG distributors, adjusting subsidised LPG prices to transportation costs and target program participation based on "LPG infrastructure readiness", i.e. preexisting (non-subsidised) LPG distribution infrastructure. Furthermore, incentivising existing actors in the kerosene supply chain to participate in the LPG infrastructure supported the fast transition (Thoday et al. 2018). Overall, the LPG conversion program in Indonesia reduced cooking kerosene use (Andadari et al. 2014; Imelda et al. 2018) and greenhouse gas emissions (Permadi et al. 2017) showed some positive health effects (Thoday et al. 2018; Imelda et al. 2018). However, the program was not properly geared towards social and health objectives, it is generally viewed as being regressive and failed to reduce the use of traditional solid fuels (Andadari et al. 2014, Toft 2016; Thoday et al. 2018).

India started a large LPG program in 2015 that provided a capital cost subsidy to poor households (e.g. Kar et al. 2019, Jose et al. 2018; (Gould 2018). While the program has increased adoption of LPG in India (e.g. Sharma et al. 2019, it has not yet achieved a sustained use of LPG and replacement of solid fuels for cooking, amplifying the need for complementary policy measures (e.g. Gould 2018); Kar et al. 2019; Mani et al. 2020). Climate impacts of switching from biomass to LPG depend on the degree of biomass combustion in stoves and the extent to which biomass originates from non-renewable sources (e.g. Singh et al. 2017; Jose et al. 2018). Barriers to increasing LPG use for cooking further included existing economic incentives, such as the abundance of solid fuels at zero (monetary) costs (e.g. Mani et al. 2020). Furthermore, additional benefits of solid fuels, such as maintaining the traditional taste of food and space heating in colder seasons, are regarded as important obstacles for extending LPG use (e.g. Gould 2018; Sharma et al. 2020).

6.4 Mitigation Options

6.4.1 Elements of Characterisation

There are many ways to characterise mitigation options. The most common metrics are technological and economic indicators, such as technology efficiencies, capital and operating costs, and mitigation costs. While important, these indicators are not sufficient to fully characterise the potential role of mitigation options. Mitigation is tightly linked with other societal priorities, including issues such as energy access, health, and poverty alleviation. More generally, people and businesses do not purchase technologies or institute operational changes based only on immediate economic costs. Other factors may inhibit and enable the implementation of mitigation options. Assessment of mitigation options must therefore extend beyond cost and technological characterisations and touch on a broader range of issues relevant to understand different enablers and barriers for implementing them. Such an assessment reveals which mitigation options can be readily implemented and which face barriers that must be overcome before they can be deployed at scale. This section characterises different options and technologies considering six dimensions (Table 6.1 Dimensions and indicators to assess the barriers and enablers of implementing mitigation options in low carbon energy systems. The relevant SDG numbers are included in parenthesis.

Table 6.1 Dimensions and indicators to assess the barriers and enablers of implementing mitigation options in low carbon energy systems. The relevant SDG numbers are included in parenthesis.

Metric	Indicators
Geophysical: Are the required resources available?	Physical potential: physical constraints to implement the option Geophysical resources (including geological storage capacity): availability of resources needed to implement the option Land use: claims on land when option would be implemented
Environmental-ecological: What are the wider environmental and ecological impacts of the options and technologies?	Air pollution (7): increase or decrease in air pollutants, such as NH_4, CH_4 and fine dust Toxic waste, ecotoxicity and eutrophication (7): changes in manure load on soil and ground water or linear consumption Water quantity and quality (6): changes in amount of water available for other uses Biodiversity (14/15): changes in area of conserved primary forest or grassland that affect biodiversity
Technological: Can the required technology be upscaled soon?	Simplicity: is the option technically simple to operate, maintain and integrate Technology scalability: can the option be scaled up, technically Maturity and technology readiness: R&D and time needed to implement to option
Economic: What economic conditions can support or inhibit the implementation of the options and technologies?	Costs in 2030 and in the long term (8): investment costs, costs in USD/tCO_2-eq Employment effects and economic growth (8): decrease or increase in jobs and economic welfare
Socio-cultural: What conditions could support or inhibit acceptability, adoption and use of the options and technologies?	Public acceptance (12/13): extent to which the public supports the option and will change their behavior accordingly Effects on health and wellbeing (3) Distributional effects (5/10/16): equity and justice across groups, regions, and generations, including energy (7), water (6) and food security (2) and poverty (1)
Institutional: What institutional conditions could support or inhibit the implementation of the option and technologies?	Political acceptance (16): extent to which politicians support the option Institutional capacity and governance, cross-sectoral coordination (16): capability of institutions to implement and handle the option Legal and administrative capacity

6.4.2 Energy Sources and Energy Conversion

6.4.2.1 Solar Energy

Solar PV is increasingly competitive with other forms of electricity generation and is the low-cost option in many applications (*high confidence*). Costs have declined by 62% since 2015 (*high confidence*) and are anticipated by an additional 16% by 2030 (*low confidence, medium evidence*) if current trends continue. Key areas for continued improvement are grid integration and non-module costs for rooftop systems (*high confidence*). Most deployment is now at utility scale (high confidence). Global future potential is not limited by insolation but by grid integration and access to finance (especially in developing countries) (*high confidence*).

The global technical potential of direct solar energy far exceeds that of any other renewable energy resource and is well beyond the total amount of energy needed to support ambitious mitigation over the current century (*high confidence*). Estimates of the global solar resource have not changed since AR5 (Lewis 2007; Besharat et al. 2013) even as precision and near term forecasting have improved (Abreu et al. 2018; Diagne et al. 2013). Approximately 120,000 TW of sunlight reaches the Earth's surface continuously, almost 10,000 times average world energy consumption; factoring in competing land use leaves a potential of 1000 EJ annually, roughly double current consumption (Dupont et al. 2020). Areas with highest solar radiation are: western South America; northern, eastern and southwestern Africa; the Arabian Peninsula and Australia (Prăvălie et al. 2019).

In many parts of the world the cost of electricity from PV is below that of fossil fuels, and in some it is below just the operating costs of fossil fuels (*high confidence*). The weighted average cost of PV in 2019 was USD 68/MWh, near the bottom of the range of fossil fuel prices (IRENA 2020d). The costs of electricity from PV have fallen by 89% since 2000 and 69% since AR5, a rate of -16% per year. The 10:90 percentile range for PV in 2019 was USD 52 to 190/MWh (IRENA 2020d). That range is due to locational differences in solar insolation, financing costs, equipment acquisition, installation labor, and other sources of price dispersion (Nemet et al. 2016; Vartiainen et al. 2020), as well as scale. For example, in India, rooftop installations cost 41% more than utility scale installations, and commercial-scale costs are 39% higher than utility-scale. Large differences in regional cost persist (Kazhamiaka et al. 2017; Vartiainen et al. 2020), with particularly low prices in China and India. Globally, the range of global PV costs overlapped almost exactly with the range of prices from coal and natural gas.

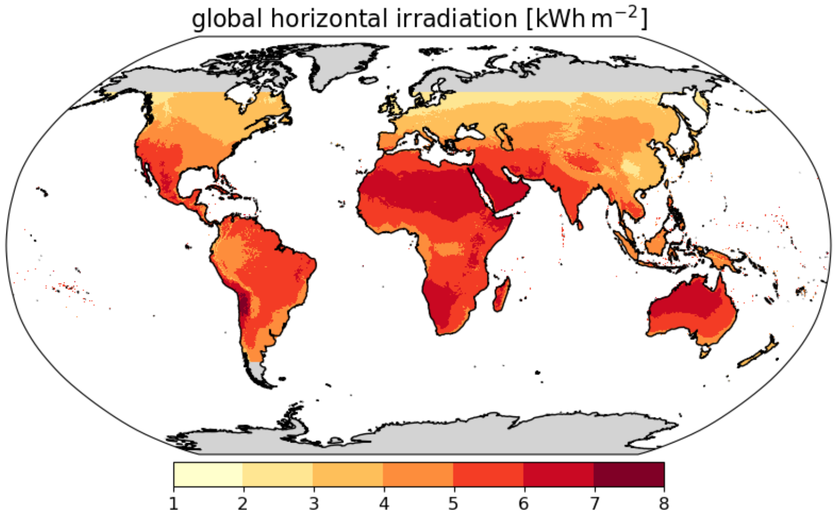


Figure 6.7 Distribution of the annual mean irradiance (GHI, kWh m^{-2}).

Source: Global solar atlas (2019).

PV costs have fallen for a variety of reasons: lower silicon costs, automation, lower margins, and a variety of incremental improvements (Fu et al. 2018; Green 2019), described in Chapter 16. An increasing share of the costs of PV electricity are in installation and related “soft costs” (marketing, permitting) rather than in the modules themselves, which now account for only 30% of installed costs (O’Shaughnessy et al. 2019; IRENA 2020d). Financing costs are an especially important barrier in developing countries (Ondraczek et al. 2015) and growth there depends on access to low-cost finance (Creutzig et al. 2017).

Concentrating solar power (CSP) costs have also fallen, albeit at about half the rate of PV: –9%/year since AR5. The lowest prices for CSP are now competitive with the more expensive range of fossil fuels, although the average CSP cost is above the fossil range. Continuing the pace of change since AR5 will make CSP competitive with fossil fuels in sunny locations, although it will be difficult for CSP to compete with PV and even hybrid PV-battery systems. CSP electricity can be more evaluable however, because CSP systems can store heat for several hours.

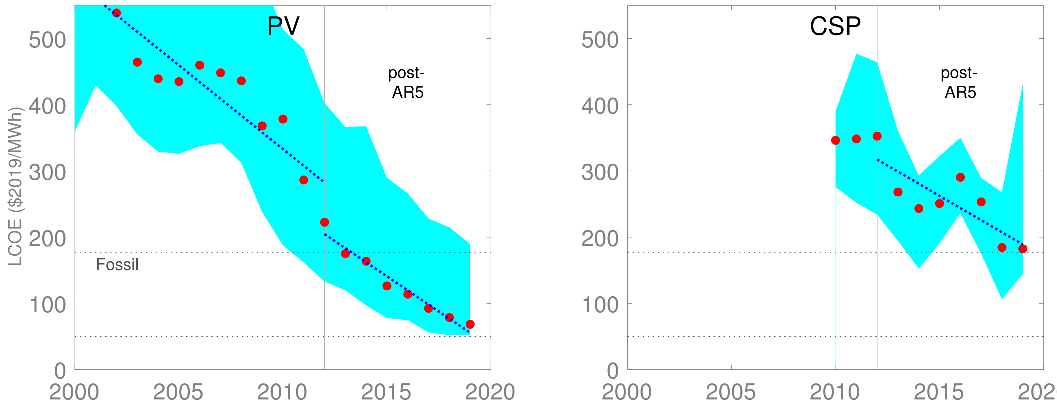


Figure 6.8 Levelised costs of electricity (LCOE) of solar energy technologies 2000–2019. Range of fossil fuel LCOE indicated as dashed lines USD 50-177/MWh. Linear fit lines applied to data for AR4-AR5 and for post-AR5 (2012). Red dots are capacity-weighted global averages for utility scale installations. Blue area shows the range between the 10th and 90th percentile in each year. Data: (Nemet 2019; IRENA 2020d).

The costs of integrating large amounts of PV in electric grids are becoming an increasing share of the total costs of PV-intensive energy systems and can be reduced by enhancing grid flexibility (*high confidence*). The full costs of PV includes grid integration, which varies tremendously due in part to: PV's share of electricity, other supply sources like wind, availability of storage, transmission capacity, and demand flexibility (Heptonstall and Gross 2020). Transmission costs can add USD 1–10/MWh or 3–33% to the cost of utility scale PV (Gorman et al. 2019). Distributed (rooftop) PV, involves a broader set of grid integration costs—including grid reinforcement, balancing, and impacts on other generation—and a larger range with integration costs of –USD 2 to USD 25/MWh, which is –3% to +37% (Hirth et al. 2015; Wu et al. 2015a; Gorman et al. 2019). Other meta-analysis put the range at USD 1–7/MWh in the USA (Luckow et al.; Wiser et al. 2017) and a comprehensive study put the range at USD 12-18/MWh for up to 35% renewables and USD 25-46/MWh above 35% (Heptonstall and Gross 2020). Increased system flexibility can reduce the integration costs of solar energy (Wu et al. 2015b) including: storage, demand response, sector-coupling (Bogdanov et al. 2019; Brown et al. 2018), and complementarity between wind and solar (Heide et al. 2010). System integration is discussed more in Section 6.4.6. Storage technologies are described in Section 6.4.3.

Because PV power plants have zero costs to run, they depress the prices in wholesale electricity markets, making it difficult to recoup investment and potentially reducing incentives for new installations (Hirth 2013). Continued cost reductions help address this issue of value deflation, but only partially. Comprehensive solutions depend on adding transmission and storage (Das et al. 2020) and more fundamentally, electricity market design (Bistline and Young 2019a; Roques and Finon 2017).

The most important ways to minimise PVs impact on the environment lie in recycling materials at end of life and making smart land use decisions (*medium confidence*). While PV's most beneficial characteristic is its minimal GHG emissions, a comprehensive assessment of its environmental impacts requires a much broader assessment including life-cycle analysis (LCA) of resource depletion, land use, ecotoxicity, eutrophication, acidification, ozone, and particulates (Mahmud et al. 2018). LCA results clearly show that solar PV lies far below fossil fuels on a CO_2/kWh basis even if they vary due to the carbon intensity of manufacturing energy and offset electricity (Grant and Hicks 2020). Concerns about systemic impacts, such as reducing the Earth's albedo by covering surfaces with dark panels, have shown to be trivial compared to the mitigation benefits (Nemet 2009). Even though GHG LCA estimates span a considerable range of 9–250 gCO_2/kWh (Kommalapati et al. 2017), their central estimates of 80 gCO_2/kWh for current cells (Hou et al. 2016) and others at 50 gCO_2/kWh (Nugent and Sovacool 2014) are an order of magnitude lower than coal and a factor of five below natural gas. Thin films and organics are half those levels, mainly because they use less material (Lizin et al. 2013) and thus avoid melting large amounts of silicon (Hou et al. 2016). Novel materials such as perovskites, discussed below, promise even lower environmental impacts, especially with improvements to their performance ratios and reliability (Gong et al. 2015). Improvements that could reduce future lifecycle impacts include higher efficiencies, longer lifetimes, sunny locations, less carbon intensive manufacturing inputs, and shifting to thin films.

Another environmental concern with large PV power plants is in the conversion of land to collect solar energy (Hernandez et al. 2015). Approximately 2 hectares of land are needed for 1 MW of solar electricity capacity (Kabir et al. 2018; Perpiña Castillo et al. 2016); at 20% efficiency, a square of PV panels of 550km per side, comprising 0.2% of Earth's land area, could meet global energy demand. While from a global perspective this share is trivial, land conversion can still have local impacts, especially near cities and where land being used for solar competes with alternative uses, such as agriculture. Substitution among renewables can reduce the extent of land conversion (Tröndle 2020). Efforts to integrate solar with these uses through agrivoltaics (the use of land for both agriculture and solar production) (Dupraz et al. 2011) show that both electricity production and food production can be compatible, for example by using shade-tolerant crops (Dinesh and Pearce 2016). Further, combining solar and agriculture can create added benefits such as income diversification, reduced drought stress, and higher solar output due to radiative cooling (Elamri et al. 2018; Hassanpour Adeh et al. 2018; Barron-Gafford et al. 2019). PV installations floating on water also avoid land use conflicts (Sahu et al. 2016). Large installations can also adversely impact biodiversity (Hernandez et al. 2014), especially where the aboveground vegetation is cleared and soils are typically graded. Landscape fragmentation creates barriers to the movement of species.

Material demand for PV will increase massively if PV deployment continues current trends, but PV materials are widely available, have possible substitutes, and can be recycled (*medium confidence*). The primary materials for PV are silicon, copper, glass, aluminum, and silver, with silicon the most costly and glass the most by mass at 70%. None of these materials are considered to be either critical or potentially scarce (IEA 2020a). Thin film cells, such as amorphous silicon and cadmium telluride, use far less material but have not yet achieved high enough efficiency and reliability to account for more than 10% of the global solar market. Quantum dots and perovskites, either on their own, or layered on silicon, have the potential to further reduce material use per energy produced.

After 30 years of use, a typical lifetime, PV modules can be recycled to prevent environmental contamination due to toxic materials contained within the cell, to reuse valuable materials, and to avoid waste accumulation. Recycling allows the reuse of nearly all—83% in one study—of the components of PV modules, other than plastics (Ardente et al. 2019) and would add less than 1% to lifecycle GHG emissions (Latunussa et al. 2016). Glass accounts for 70% of the mass of a solar cell and is relatively easy to recycle. Recycling technology is advancing with several firms participating, but the industry's scale and share recycled are still small (Li et al. 2020c). By 2050 however, end use PV could total 80 MT, 10% of global electronic waste (Stolz and Frischknecht 2017). The International Energy Agency runs a program to enable PV recycling by sharing best practices about minimising life cycle impacts of the recycling process itself Ensuring that a substantial amount of panels are recycled at end of life will likely require policy incentives, as the market value of the recovered materials, aside from aluminum and copper, is likely to be too low to justify recycling on its own (Deng et al. 2019). A near term priority is maximising recovery of silicon, the most valuable material component of PV (Heath et al. 2020).

A wide variety of alternative PV materials are improving in efficiency and stability, providing longer term pathways for continued PV costs reductions and better performance (*high confidence*). While solar PV based on semi-conductors constructed from wafers of silicon still captures 90% of the market, new designs and materials have the potential to reduce costs further, increase efficiency, reduce resource use, and find new applications. Within silicon PV, the most important technological advance in the past

10 years has been the widespread adoption of the passivated emitter and rear cell (PERC) design (Green 2015), now accounting for a third of production, which boosts efficiency over traditional aluminum backing by increasing reflectivity within the cell and reducing electron hole recombination (Blakers 2019). Bifacial modules increase efficiency by making use of reflected light from the ground or roof on the back side of modules (Guerrero-Lemus et al. 2016). Integrating PV into buildings can reduce overall costs and improve building energy performance (Shukla et al. 2016). Concentrating PV uses lenses or mirrors that collect and concentrate light onto high efficiency PV cells (Li et al. 2020a). Beyond crystalline silicon, thin films of amorphous silicon, cadmium telluride, and copper indium gallium selenide (among others) have the potential for much lower costs while their efficiencies have been increasing (Green et al. 2019). Quantum dots, spherical semi-conductor nano-crystals, can be tuned to absorb specific wavelengths of sunlight given the potential for high efficiency with very little material use (Kramer et al. 2015). Perovskites, inexpensive and easy to produce mineral structures, have increased in efficiency by a factor of six in the past decade; the biggest challenge is light-induced degradation (Petrus et al. 2017; Chang et al. 2018; Wang et al. 2019b; Zhu et al. 2020). Hybrids of silicon with layers of quantum dots and perovskites have the potential to take advantage of the benefits of all three, although those designs require that these new technologies have stability and scale that match those of silicon (Palmstrom et al. 2019; Chang et al. 2017). This broad array of alternatives to making PV from crystalline silicon offer realistic potential for lower costs, reduced material use, and higher efficiencies in future years.

Concentrating solar power (CSP) can provide distinct services in high temperature heat and diurnal storage, even if it is more costly than PV and its potential for deployment limited (*medium confidence*). CSP use reflective surfaces, such as parabolic mirrors, to focus sunlight on a receiver in order to heat a working fluid, which is subsequently transformed into electricity (Islam et al. 2018). Solar heating and cooling are also well established technologies, and solar energy can be utilised directly for domestic and/or commercial applications such as drying, heating, cooling, and cooking (Ge et al. 2018). Solar chimneys heat air using large transparent greenhouse-like structures and channel the warm air to turbines in tall chimneys (Kasaeian et al. 2017). Solar energy can also be used to produce solar fuels, for example, hydrogen or synthetic gas (syngas) (Nocera 2017; Montoya et al. 2016; Detz et al. 2018). In addition, research proceeds on space-based solar PV which takes advantage of high insolation and a continuous solar resource (Kelzenberg et al. 2018), but faces the formidable obstacle of developing safe, efficient, and inexpensive microwave or laser transmission to the Earth's surface (Yang et al. 2016). Of these solar alternatives to PV, CSP is the most widely adopted.

Like PV, CSP can deliver large-scale power plants (up to 200 MW per unit) and can maintain substantial thermal storage, which is valuable for load balancing over the diurnal cycle (McPherson et al. 2020). However, unlike PV, only direct sunlight can be concentrated for electricity generation in CSP, constraining its cost-effectiveness to North Africa, Middle East, Southern Africa, Australia, the Western U.S., parts of South America (Peru, Chile), the Western Part of China, and Australia (Deng et al. 2015; Dupont et al. 2020). Parabolic troughs, central towers and parabolic dishes are the three main solar thermal technologies currently deployed (Wang et al. 2017d). Parabolic troughs represented approximately 70% of new capacity in 2018 with the balance made up by central tower plants (Islam et al. 2018). Especially promising research directions are on tower-based designs which can achieve high temperatures, useful for industrial heat and energy storage (Mehos et al. 2017), as well as direct steam generation designs (Islam et al. 2018). Costs of CSP have fallen by nearly half since AR5 (Figure 6.9), albeit at a slower rate than PV. Since AR5, almost all new CSP plants have storage (Thonig 2020).

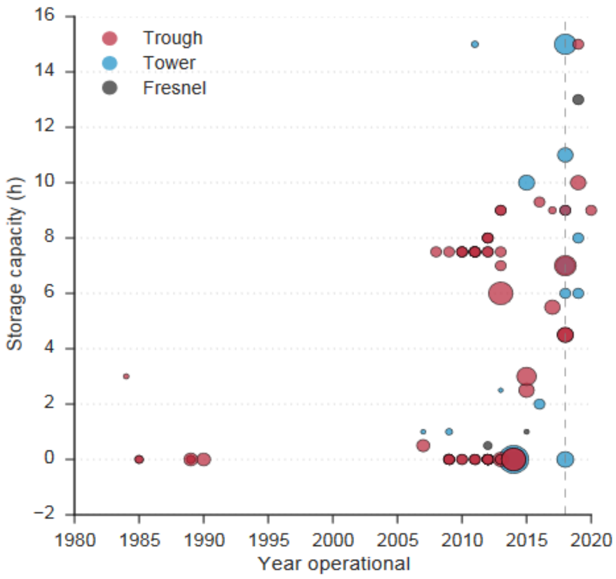


Figure 6.9 Since AR5, almost all new CSP plants have storage (Thonig 2020) Data: https://csp.guru/metadata.html.

Solar energy elicits favorable public responses in most countries (*high confidence*) (Bessette and Arvai 2018; Hanger et al. 2016; Jobin and Siegrist 2018; Ma et al. 2015; Mcgowan and Sauter 2005; Hazboun and Boudet 2020). Solar energy is perceived as clean and environmentally friendly few downsides (Faiers and Neame 2006; Whitmarsh et al. 2011b). Key motivations for homeowners to adopt photovoltaic systems are expected financial gains, environmental benefits, the desire to become more self-sufficient, and peer expectations (Korcaj et al. 2015; Palm 2017; Vasseur and Kemp 2015). Hence, observability of photovoltaic systems can facilitate adoption (Boudet 2019). The main barriers to adoption of solar PV by households are its high upfront costs, aesthetics, landlords, and concerns about performance and reliability (Whitmarsh et al. 2011b; Vasseur and Kemp 2015; Faiers and Neame 2006).

6.4.2.2 Wind Energy

Wind power is increasingly competitive with other forms of electricity generation and is the low-cost option in many applications (*high confidence*). Costs have declined by 23% and 32% on land and offshore since 2015 (*high confidence*) and further improvements can be expected by 2030 (*medium confidence*) if current trends continue. Key areas for continued improvement are technology improvements and economies of scale (*high confidence*). Global future potential is largely limited by land availability in wind power-rich areas, lack of supporting infrastructure, grid integration and access to finance (especially in developing countries) (*high confidence*).

Energy from wind is abundant and the estimated technical potentials surpass the total amount of energy needed to support ambitious mitigation over the coming century (*high confidence*). Energy from wind near the Earth’s surface is abundant. Because of geographical location and topography, wind resources are very unevenly distributed over the globe and the time of the year (Petersen and Troen 2012), but potential hotspots exist on every continent (Figure 6.10). Technical potentials for wind power onshore vary considerably, often because of inconsistent use of suitability factors (McKenna et al. 2020). Without considering these land use restrictions, about 3% of the world’s land area has excellent wind resources (Bandoc et al. 2018). Offshore wind power offers even larger potential because winds there are stronger and more reliable (Bosch et al. 2018), but exploitation is more expensive because of higher costs for construction, maintenance and transmission of electricity. Studies have suggested that ‘bottom-up’ estimates of wind physical potentials could be overestimated (Miller et al. 2015; Volker et al. 2017; Kleidon and Miller 2020), but even in the most conservative estimates the technical wind potential surpasses the amount required for climate mitigation (Bosch et al. 2017; Eurek et al. 2017). In some regions interannual variations in wind energy resources should be considered when designing an optimal power system (Wohland et al. 2019a; Coker et al. 2020).

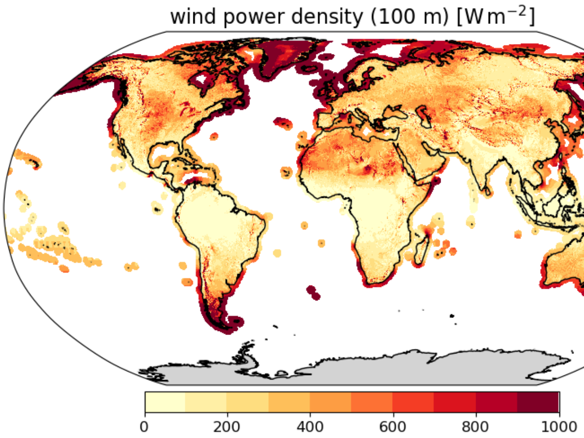


Figure 6.10 Mean wind power density [Wm^{-2}] at 100 m above ground level over land and 100 km offshore.

[Source: DTU Global Wind Atlas https://globalwindatlas.info/].

Larger, taller and more efficient wind turbines have resulted in larger capacity factors and lower installed costs for wind farms in the past 5 years (*high confidence*). Newer floating foundations could potentially revolutionise wind power exploitation offshore. Improvements in wind turbine technologies, and wind power cost reductions, are driven mainly by larger capacity turbines as well as larger rotor diameters and hub heights; larger swept areas lead to increased capacity factors for a given wind resource, while wind resources increase with height. All major onshore wind markets have seen rapid growth in both rotor diameter (from 81.2 m in 2010 to 110.4 m in 2018), and average power ratings (from 1.9 MW in 2010 to 2.6 MW in 2018). The average size of offshore wind turbines grew by a factor of 3.4 in less than two decades, from 1.6 MW in 2000 to 5.5 MW in 2018 (IRENA 2020a). The largest turbine in the world became operational offshore in the Belgian coast in 2020, an 9.5 MW turbine with a rotor diameter of 164 m. Floating foundations could potentially revolutionise wind power exploitation offshore by allowing the taping into the abundant wind potential in deeper waters. This type of technology is particularly important for regions like southeast Asia and western North America, where coastal waters are too deep for fixed-bottom wind turbines. Floating wind farms offer economic and environmental benefits compared with fixed-bottom designs due to less-invasive activity on the seabed during installation, but meteorological conditions further offshore are harsher on wind turbine components (IRENA 2019a).

A clear trend to higher capacity factors for wind farms can be seen since 2010 (Figure 6.10). The capacity factor for onshore wind increased by almost one-third, from 27% in 2010 to 36% in 2019, and for offshore wind from 37% in 2010 to 44% in 2019 (IRENA 2020a). These improvements come from the evolution in capacity, size, and rotor diameter, but also in functionality. For example, manufactures can adapt the wind turbine generator to the wind conditions. Turbines for windy sites have smaller generators and smaller specific capacity per rotor area. Consequently, modern wind turbines operate more efficiently and provide higher capacity factors (Rohrig et al. 2019).

On one hand, developments in wind turbine control, including variable speed control, reduce fatigue and limit loads on the wind turbine structure in certain situations. Forecasting (using big data and AI) and the automatic regulation of turbines (pitch control and yaw control) are used to maximise the overall energy output. On the other hand, there are also ongoing developments to cover the integration of dynamic active and reactive power control functions. These functions make use of the grid side dynamic control capabilities of wind turbines that allow for stabilisation of the grid, thereby allowing for higher penetration of wind power in the existing power grids (Rohrig et al. 2019).

Onshore wind is now consistently undercutting fossil fuels in a growing number of markets, often by a substantial amount (*high confidence*). The country-level weighted average LCOE for new projects commissioned in 2019 was lower than the cheapest fossil fuel-fired option in Argentina, where the weighted-average LCOE was USD 0.049/kWh, as well as in Brazil (USD 0.048/kWh), China (USD 0.047/kWh), Egypt (USD 0.049/kWh), India (USD 0.049/kWh), Finland (USD 0.039/kWh), Sweden and the U.S. (both at USD 0.046/kWh).

Total installed costs for both onshore and offshore wind farms have decreased since 2015 (Figure 6.11), but the total installed costs for onshore wind projects are very site- and market-specific as reflected in the spread. China, India and the U.S. have experienced the largest declines in total installed costs. In 2018, typical country-average total installed costs were around USD 1,200/kW in China and India, and between USD 1,660 and USD 2,250/kW elsewhere (IRENA 2019b). Total installed costs of offshore wind farms declined by 18% between 2010 and 2019. But, because some of the new offshore wind projects have moved to deeper waters and further offshore, there are considerable year-to-year variations in their price (IRENA 2019a). Projects in recent years have typically been built in deeper waters (10–55 m) and up to 90 km offshore, compared to around 10 m in 2001–2006, when distances rarely exceeded 20 km. With the shift to deeper water and sites further from ports, the total installed costs of offshore wind farms rose, from an average of around USD 2,500/kW in 2000 to around USD 5,400/kW by 2011–2014, before falling to around USD 4,350/kW in 2018. Total costs are higher in Europe than in China, reflecting the fact that Chinese deployment to date remains in shallow waters, close to ports. System integration costs, which are not included in LCOE, are presented in Section 6.4.3.

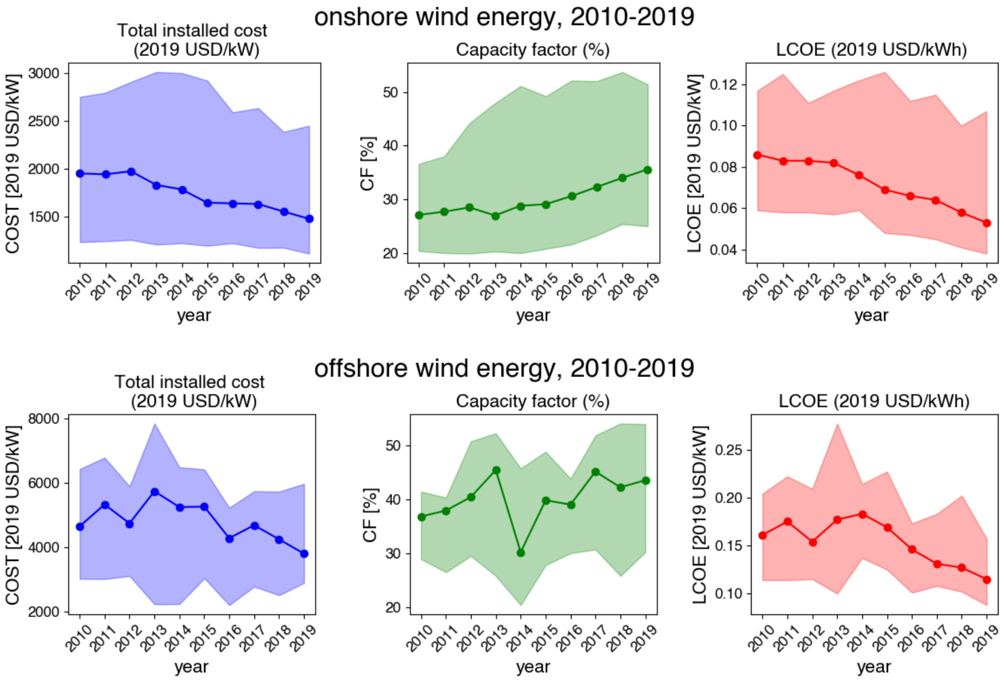


Figure 6.11 Global weighted average total installed costs, capacity factors and LCOE for onshore (top) and offshore (bottom) wind power, 2010-2019.

Source: (IRENA 2020a).

Wind power development poses relatively low, but sometimes locally significant ecological issues (*high confidence*). The most important measure for managing environmental and social impacts is careful site selection of wind power facilities. The environmental impact of wind technologies, including CO_2

emissions, is concentrated mainly in the manufacturing, transport and building stage and to a smaller extent in the disposal stage, but is at a minimum in the operational/use stage. Impact per generated power is strongly influenced by the operating lifetime, quality of wind resource, conversion efficiency and size of the wind turbines (Laurent et al. 2018). All wind power technologies repay their carbon footprint in less than a year (Bonou et al. 2016), providing decades of zero-emission energy.

Wind farms can cause local ecological impacts, including impacts on animal habitat and movements, biological concerns, bird/bat fatalities from collisions with rotating blades, and health concerns (Morrison and Sinclair 2004). The impacts on animal habitats and collisions can be resolved or reduced through selective stopping program without affecting the productivity of the wind farm (de Lucas et al. 2012). Many countries now require environmental studies of impacts of wind turbines on wildlife prior to project development, and, in some regions, shutdowns are required during active bird migration (de Lucas et al. 2012). Offshore wind farms can also impact migratory birds and other sea species (Hooper et al. 2017), and floating foundations pose lower environmental impacts at build stage (IRENA 2019a). The impacts of wind farm noise on long-term human health have been shown to be well below detectable levels (Poulsen et al. 2018).

There is generally high support for onshore and even higher support for offshore wind energy, although people may oppose specific wind farm projects (*high confidence*) (e.g., Rand and Hoen 2017; Steg 2018; Bell et al. 2005; Batel and Devine-Wright 2015). People generally believe that wind energy is associated with environmental benefits and is relatively cheap. Yet, some people believe wind turbines can cause noise and visual aesthetic pollution, threaten areas of symbolic values (Devine-Wright 2005), and can have adverse effects on wildlife (Bates and Firestone 2015), which challenges public acceptability (Rand and Hoen 2017). Public acceptability of local wind projects is higher when people believe fair decision-making procedures have been implemented (Aitken 2010a; Dietz and Stern 2008). Yet, the evidence for effects of distance to wind turbines on public acceptability and whether financial compensation can help increase support is mixed (Hoen et al. 2019; Rand and Hoen 2017). Offshore wind farms projects have higher public support, but are not free from public acceptance issues (Rudolph et al. 2018; Bidwell 2017). In the financial context, common barriers to wind development are high initial cost of capital and long payback periods and lacking or inadequate access to capital and high upfront capital costs. Optimal wind energy expansion will occur in the presence of a political commitment to establish, maintain, and improve financial support instruments, technological efforts to support a local supply chain, and, especially, grid reinforcements, including storage (Section 6.4.6), to integrate this new decentralised way of generating electricity (Diógenes et al. 2020).

6.4.2.3 Hydroelectric Power

Hydropower is technically mature, proved worldwide and may be used to balance electricity supply. Areas for improvement are to be found mostly during the planning of a hydropower plant to minimise environmental and social impacts as well as developing virtual storage capacity by the spatio-temporal coordination of hydropower plants at long distances. (*high confidence*)

The estimation of global gross theoretical available hydropower potential varies from 31 to 128 PWh yr^{-1}, exceeding total electricity production in 2018 (Banerjee et al. 2017), but only a portion of this potential is accessible (*high confidence*). Hoes et al. (2017) estimates the gross theoretical hydropower potential to be approximately 52 PWh yr^{-1}, over 11.8 million locations (Figure 6.12). This is about one tenth of the global primary energy in 2019 (BP, 2020). On the other hand, the electricity generation by hydropower plants in 2019 was about 16% of the global electricity (BP, 2020); (Killingtveit 2020). Hydropower has a significant potential in the future energy mix, although many of the locations cannot be developed for (current) technical, economic or political reasons. Hydropower has a technical potential estimated between 8 and 30 PWh yr^{-1}, and an economic potential of 8 to 15 PWh yr^{-1} (van Vliet et al. 2016a; Zhou et al. 2015). The greatest contributor to the hydropower potential is Asia (48%), followed by S. America (19%) (Hoes et al. 2017). According to the World Energy Council, there may be an available potential of hydroelectric generation worldwide of 10 PWh yr^{-1}. This represents approximately 40% of the total electricity supplied during 2018.

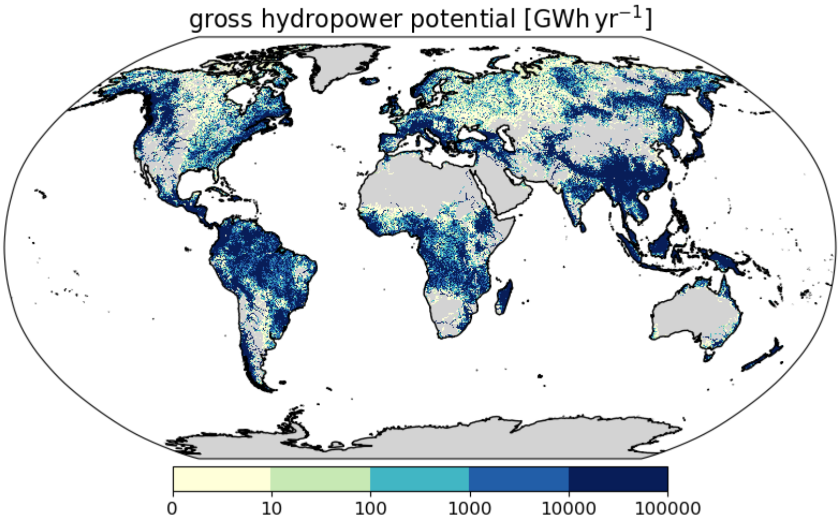


Figure 6.12 Global map of gross hydropower potential distribution [GWh yr^{-1}].
Original source: Hoes et al (2017).

Hydropower is a mature technology that is well-proven worldwide with local adapted solutions (*high confidence*) (Zhou et al. 2015; Killingtveit 2020). The efficiency of hydroelectric plants is greater than 85%. A hydropower plant typical has a water intake, the power station and the water outlet. Water intake and outlet in a power plant may be divided in two major groups connected to the water storage: without water storage (run-off-river, and hydrokinetic) and with water storage (storage hydro, pumped storage) (Killingtveit 2020, IRENA 2015a). Hydropower plants without or with small storage can produce a few kWs to 10 MWs. These facilities are useful to provide electricity for a household up to small communities (El Bassam et al. 2013; Towler 2014). The lack of storage makes such hydropower plants susceptible to climate variability, especially droughts, when the amount of water may not be enough to keep generation (Section 6.5, Premalatha et al. 2014).

Hydropower plants with large reservoir are often large ones with generation up to several GW. Such hydropower plants require large areas for their reservoir; however, this storage provides flexibility and allows the hydropower to adapt to demand profile, increase reliability and continuity in the electricity grid. It can be used as a peak load to reduce the costs derived from the dispatch of the most expensive plants, as well as their reservoirs being a source for other water demand uses (Jacobson et al. 2015). A pumped storage hydropower store energy by pumping water to higher reservoirs during low-demand periods (Killingtveit 2020). The regulatory characteristics of the storage of the hydropower plants on the electricity system can be experienced

Hydropower is one of the lowest-cost energy technologies (Mukheibir 2013). Once the hydropower station is constructed, costs for operation and maintenance are quite low, typically of 2% – 2.5% of the investment costs per kW per year for a lifetime of 40 to 80 years (Killingtveit 2020). Upfront costs related to the construction of the hydropower plant are high and site specific. The total cost for an installed large hydropower project varies from as low as USD 1000/kW up to about USD 8000/kW if the site is located far away from transmission lines, roads and infrastructure. Investment costs increase for small hydropower plants and may be as high as USD 10000/kW or more for the installation of plants of less than 1 MW (IRENA 2015a). During the past 5 years total installed costs and LCOE have risen by a few percent, but the LCOE of hydropower remains lower than the cheapest new fossil fuel-fired cost option (IRENA 2019c). However, social and environmental costs associated to the hydropower plants are important to be taken into consideration during the planning of the hydropower plant for the definition of the real cost of the generated electricity (Moran et al. 2018).

Hydroelectric power plants may pose serious environmental and societal impacts that need to be managed carefully (*high confidence*) (Mccartney 2009). Hydropower dams and channels may obstruct fish migration and cause large modification to aquatic habitats. Below the hydropower dam, there can be considerable alterations to vegetation, natural river flows, retention of sediments and nutrients, and alterations to water quality and temperature. Construction of large reservoirs leads to loss of land, that in its turn may lead to social and environmental consequences. During the planning stage of a power plant local physical, environmental, climatological, social and political aspects should be taken into consideration and adapted to the local needs considering a broad perspective (Killingtveit 2020). Moreover, a virtual energy storage that results from the spatio-temporal coordination of hydropower at long distances can compensate eventual climate-driven fluctuations on the electricity generation by virtually multiplying the existing physical storage capacity (Wörman et al. 2020).When large areas of land are flooded by dam construction, greenhouse gas emissions are significant and often more than those from natural lakes (Phyoe and Wang 2019; Maavara et al. 2020).

Public support for hydroelectric energy is generally high (Steg 2018), and higher than support for coal, gas, and nuclear. Yet, public support of hydro seems to differ for existing and new projects (*high confidence*). Public support is generally high for small and medium scale hydropower in regions where hydropower was historically used (Gormally et al. 2014). Similarly, there is high support for existing large hydropower projects in Switzerland (Plum et al. 2019; Rudolf et al. 2014), Canada (Boyd et al. 2019), and Norway (Karlstrøm and Ryghaug 2014), where this is a trusted and common energy source. Yet, public support seems lower for new hydropower projects (Hazboun and Boudet 2020); the construction of new large hydropower plants is met with strong resistance in some areas, such as Chile (Bronfman et al., 2015; Vince, 2010). People generally perceive hydroelectric energy as clean, and not contributing to climate change and environmental pollution (Kaldellis et al. 2013). For example, in Sweden, people believed that existing hydropower projects have as little negative environmental impacts as solar and less than wind (Ek 2005). However, in areas where the construction of new large-scale hydroelectric energy is met with resistance, people believe that electricity generation from hydro can cause environmental, social, and personal risks (Bronfman et al., 2012; Kaldellis et al., 2013).

The construction time of hydroelectric power plants is longer than many other renewable technologies, reaching up to 7 years, which implies that there is greater uncertainty in the completion of the project. As a result of social and environmental constraints only a small fraction of the economic potential can be developed, especially in developed countries. Many developing countries have major undeveloped hydropower potential, and there are opportunities to develop hydropower combined with other economic activities such as irrigation (Lacombe et al. 2014). Competition for hydropower across country borders could also be a forcing for conflict, especially under climate change impact in water resources (Ito et al. 2015).

6.4.2.4 Nuclear Energy

Nuclear power remains a viable option to deliver low-carbon energy at scale (*high confidence*). Doing so will require improvements in managing construction projects of proven reactor designs that hold the promise of lower costs and broader use (*medium confidence*). At the same time, nuclear power continues to be beset by cost overruns, high up-front investment needs, challenges with ultimate disposal of radioactive waste, and low public acceptance and political support, which has only decreased since the Fukushima Daiichi accident (*high confidence*).

It is unlikely that resource scarcity will provide a constraint to nuclear deployment at meaningful scales for climate mitigation (*medium confidence*). Estimates for identified uranium resources have been increasing steadily over the years: at the 2016 level of uranium requirements (62,825 tU), identified conventional resources are estimated to over 130 years of supply as compared to 100 years remaining estimated in 2009 (OECD NEA and IAEA 2010; OECD NEA and IAEA 2019). In an unlikely case of uranium resource scarcity in the future, uranium's alternative – thorium - might regain interest, which has waned in the face of a better understanding of uranium deposits, their availability and low prices (OECD NEA 2015; IAEA 2005).

Gen III nuclear power is already an established technology, but there are several other technology options available in the 2030-2050 planning horizon (*medium confidence*). Reactor designs are frequently classified into four generations. The first commercial nuclear reactors built in the late 1950s and 1960s are classified as Generation-I systems. Generation-II systems include commercial reactors that were built from 1970 to 1990. Generation-III reactors are commercial designs that incorporate evolutionary improvements over Generation-II systems. Generation-IV is the classification used to describe a set of advanced reactor designs that use non-water coolants and are under development today.

- **New Builds - GEN III / III+**. The nuclear industry has entered a new phase of reactor construction, based on evolutionary designs of Gen III/III+. These reactors achieve improvements over previous designs through small to moderate modifications, including improved redundancy, increased application of passive safety systems, and significant improvements to containment design to reduce the risk of a major accident. Examples include European - EPR, Korean - APR1400, U.S. - AP1000, Chinese - HPR1000 or Russian - VVER-1200 (MIT 2018).
- **Long-term operation (LTO) of the current fleet**. Continued production from nuclear power will depend in part on extensions of the existing fleet. At the end of 2019, two thirds of nuclear power reactors have been operational for over 30 years. The design lifetime of previous generation reactors is typically 40 years. Engineering assessments have established that reactors can operate safely for longer if key components (e.g. mechanical and electrical equipment, instrumentation and control facilities, cooling towers) are replaced or refurbished (IAEA 2018). The lifetime extension considered in most of the countries is 10 to 20 years (OECD IEA NEA 2020).
- **Small Modular Reactors**. There are more than 70 SMRs designs at different stages of consideration and development, from conceptual phase to licensing and construction of FOAK facility (IAEA 2020). SMRs are expected to offer lower overall investment (units of less than 300 MW) than traditional nuclear power stations. Modularity and off-site pre-production should allow greater efficiency in construction, shorter delivery times, and overall cost optimisation (IEA 2019b) Most SMR designs offer increased load-following capability that makes them suitable to operate in smaller systems and in systems with increasing shares of variable renewable sources. Their market development by the early 2030s will strongly depend on the successful deployment of prototypes during 2020s which can demonstrate the announced benefits.

Nuclear power costs vary substantially across countries. Nuclear has proven economically competitive in some countries and uncompetitive in others (*high confidence*). First-of-a-kind (FOAK) GEN III/III+ projects under construction in Northern America and Europe were marked by delays and costs overruns (Berthelemy and Rangel 2015) – with Finland and France as the extreme cases - where construction times exceed 13-15 years and cost surpass 3-4 times the initial budgets (OECD IEA NEA 2020). In contrast, recent projects in China and Korea have been executed within 6 years. In addition to region-specific reasons, future nuclear GEN III/III+ costs will depend on the ability to benefit from the accumulated experience to control main cost drivers. These fall into four categories: design maturity, effective project management, regulatory stability and predictability and multi-unit and series effect (NEA 2020). With lesson learned from FAOK projects, the cost of electricity for new builds are expected to be in the range of USD 42 and 102/MWh depending on the region, similar to cost estimates in 2015 (OECD IEA NEA 2020).

Lifetime extensions are significantly cheaper than new builds and cost competitive with other low-carbon technologies. The overnight cost of lifetime extensions is estimated in the range of USD 390 -

630/kWe for Europe and North America, or USD 30–36/MWh for extensions of 10 to 20 years (OECD IEA NEA 2020).

The first U.S. small-scale nuclear power project NuScale announced a capital cost of less than USD 5,100/kWe, which would not be competitive in the U.S. given current natural gas prices (Capellán-Pérez et al. 2017). Cost-cutting opportunities, for SMRs and GEN III/III+ reactors, such as design standardisation and innovations in construction approaches, are expected to make these technologies competitive with other low-carbon options by 2030 (*medium confidence*).

Nuclear power is attended by a range of environmental and ecological impacts (*high confidence*). New passive reactor designs have nevertheless further reduced the risk of such accidents (*high confidence*). Although low in volume, it results in radioactive waste entailing strictly controlled disposal. On a global scale, roughly 421 ktons of spent nuclear fuel have been produced since 1971 (IEA 2014). Out of this volume, 2–3% is high-level radioactive waste (HLW), which presents challenges in terms of radiotoxicity and longevity and requires permanent disposal. Furthermore, despite low probabilities, the potential for major nuclear accidents exists, and the radiation exposure impacts could be very large and long-lasting (Steinhauser et al. 2014). Nuclear energy is generally found to be favorable regarding land occupation (Cheng and Hammond 2017; Luderer et al. 2019) and ecological impacts (Brook and Bradshaw 2015; Gibon et al. 2017) although the upstream nuclear life cycle (i.e., mining, tailings) can impact biodiversity locally. Similarly, requirements of bulk materials per unit of energy produced are low (e.g. aluminum, copper, iron, rare earth metals) (Luderer et al. 2019). Depending on the choice of cooling system (once-through or closed cycle) (Mouratiadou et al. 2016), nuclear power can require large amounts of water (Meldrum et al. 2013). In general, power plants situated on the coast are typically more immune to water scarcity issues and regulations on water discharges. On the other hand, water intensive inland nuclear power plants may contribute to localised water stress and exacerbate conflicts among competing water uses in those areas (Fricko et al. 2016). Life cycle assessment (LCA) studies suggest that the overall impacts on human health (in terms of disability adjusted life years (DALYs) from nuclear power are substantially lower than those caused by fossil fuel technologies and are comparable to renewable energies (Treyer et al. 2014; Gibon et al. 2017). It commonly represents an end point level in LCA methods linked quantitatively with the most common midpoint impact categories such as human toxicity, ionizing radiation, ozone layer depletion, particulate matter formation and photochemical oxidant formation.

Nuclear power continues to suffer from limited public and political support (*high confidence*). Public support for nuclear energy is consistently lower than for renewable energy and natural gas, and in many countries as low as support for energy from coal and oil (Hobman and Ashworth 2013; Corner et al. 2011; Pampel 2011). The major nuclear accidents (e.g., Three Mile Island, Chernobyl, Fukushima) contributed to the decrease in public support (Bird et al., 2014; Poortinga, Aoyagi, & Pidgeon, 2013). Public remains concerned about the safety risks of nuclear power plants and radioactive materials (Tsujikawa et al. 2016; Bird et al. 2014; Pampel 2011).

At the same time, nuclear energy is seen in some quarters as a reliable energy source, beneficial for the economy and helpful in climate change mitigation. People who strongly endorse self-interest values are more likely to perceive such benefits of nuclear energy (Groot et al. 2013). Public support for nuclear energy is higher when people are concerned about energy security, including concerns about the availability of energy and high energy prices (Gupta et al. 2019b). Public support also increases when trust in managing bodies is higher (de Groot and Steg 2011). Similarly, transparent and participative decision-making processes enhance perceived procedural fairness and public support (Sjoberg 2004).

Because of the sheer scale of the investment required (individual projects can exceed USD 10 billion in value), nearly 90% of nuclear power plants under construction are run by state-owned companies with governments assuming most of the risks and costs. For countries that choose nuclear power in their energy portfolio, stable political conditions and support, clear regulatory regimes, and adequate financial framework are crucial for successful implementation. Nuclear power's low carbon attributes are typically not compensated in the way that wind and solar power are promoted, for example, through feed-in-tariffs and feed-in premiums widely applied in the EU (Kitzing et al. 2012) or renewable portfolio standards in the U.S. (Barbose et al. 2016). These out-of-market payments create distortions in the wholesale electricity price (leading occasionally to low or even negative prices), which impact the revenues of existing nuclear plants (Bruninx et al. 2013; Newbery et al. 2018; Lesser 2019). Nuclear power's long-term viability will hinge on demonstrating to public and investors that there is a long-term solution to spent nuclear fuel. Evidence from countries steadily progressing towards first permanent disposals - Finland and Sweden - suggests that broad political support, coherent nuclear waste policies and a well-managed, consensus-based decision-making process are critical for accelerating this process (Metlay 2016; Fountain 2017). The framework to address concerns about proliferation of nuclear weapons is in place since many decades. Nuclear projects must comply with national and international norms and rules, such as IAEA guidelines, international treaties and conventions, and other industry standards (OECD IEA NEA 2020).

6.4.2.5 Carbon Dioxide Capture, Utilisation, and Storage

Since AR5, there has been an increased thrust on novel CCUS platforms that reduce energy penalty associated with CO_2 capture, development of CO_2 utilisation pathways as a substitute to geologic storage and global policy developments (*high confidence*).

Global geologic storage potential is about 10000 Gt-CO_2, with more than 80% of this capacity existing in saline aquifers (*medium confidence*). Not all the sink capacity is uniformly usable since geologic and engineering factors limit the actual sink to an order of magnitude below the theoretical potential, which is still more than the CO_2 sink requirements through 2100 to limit temperature change to 1.5°C (*high confidence*). One of the key limiting factors associated with geologic CO_2 storage is sink availability, which is not uniformly distributed globally (Figure 6.13). The vast majority of the available sink capacity exists in saline aquifers. Capacity in oil and gas reservoirs and coalbed methane fields is limited. Storage potential in the U.S. alone is >1000 Gt-CO_2, which is more than 10% of the world total (NETL 2015). The Middle East has more than 50% of global enhanced oil recovery potential (Selosse and Ricci 2017). Moreover, not all the geologic sinks are utilisable. For economic long-term storage, the desirable conditions are depth of 800-2500 m, thickness of greater than 50 m and permeability greater than 500 mD (Singh et al. 2020). Even in reservoirs with large storage potential, the rate of injection might be limited by the subsurface pressure of the reservoir (Baik et al. 2018a). In many cases, geologic storage capacity is not located close to the CO_2 source, which might further reduce the viable capacity (Garg et al. 2017a).

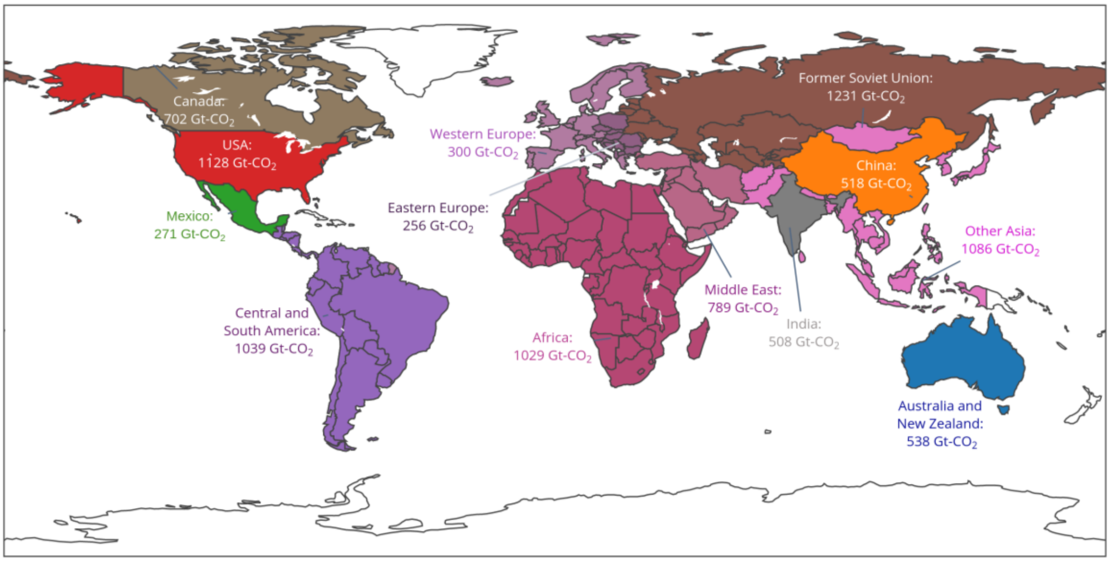


Figure 6.13 Geologic storage potential across underground formations globally
[Data from (Selosse and Ricci 2017)]

CO_2 utilisation – instead of geologic storage - might present a more viable and acceptable method of decarbonisation (*high confidence*). The global CO_2 utilisation potential, however, is limited to 1-2 Gt-CO_2 yr^{-1} currently (Hepburn et al. 2019; Kätelhön et al. 2019) and might increase to 20 Gt-CO_2 by the mid-century (*medium confidence*). CCU involves using CO_2 as a feedstock to synthesise products of economic value. It is notable that the highest potential for CCU exists in sectors that deliver energy products themselves, e.g. methanol, microalgae and methane. However, these represent endothermic reaction with large energy consumption (Hoppe et al. 2018; Daggash et al. 2018). Moreover, when carbon-rich fuel end-products are combusted, significant proportions of CO_2 get emitted back into the atmosphere. Accordingly, several CO_2 utilisation avenues might be limited by energy availability. Because of presence of several industrial corridors globally, a number of regions demonstrate locations where CO_2 utilisation potential could be matched with large point sources of CO_2. (Wei et al. 2020).

Existing post-combustion approaches relying on absorption are technologically ready for full-scale deployment (*high confidence*). More novel approaches using membranes and chemical looping might reduce the energy penalty associated with absorption are in the laboratory or prototype phase of development (Abanades et al. 2015) (*high confidence*). There has been significant progress in post-combustion capture technologies that used absorption in solvent such as monoethanol amine (MEA) with commercial-scale application at two facilities – Boundary Dam since 2015 and Petra Nova since 2017 with capacity of 1 and 1.6 Mt-CO_2 yr^{-1} respectively (Mantripragada et al. 2019). Several 2nd and 3rd generation capture technologies are being developed with the aim of not just lowering costs but also enhancing advantages such as improved ramp-up and lower water consumption. These include processes such as chemical looping, which also has the advantage of ready co-firing amenability with biomass (Bhave et al. 2017; Yang et al. 2019)Another important technological development is the NET Power cycle which utilised CO_2 as a working fluid and operates based on oxy-combustion capture. These can deliver net efficiencies greater than 50% and 100% CO_2 capture but are quite sensitive to oxygen and CO_2 purity needs (Scaccabarozzi et al. 2016; Ferrari et al. 2017).

The technological development for CO_2 utilisation is still in the laboratory, prototype, and pilot phases. Technology development in some end-uses is limited by purity requirements for CO_2 as a feedstock (*high confidence*). The efficacy of CCU processes depends on additional technological constraints such as CO_2 purity and pressure requirements. For instance, urea production requires CO_2 pressurised to 122 bar and purified to 99.9%. While most utilisation pathways require purity levels of 95-99%, algae production may be carried out with atmospheric CO_2 (Ho et al. 2019; Voldsund et al. 2016).

CO_2 capture costs present a key challenge, remaining higher than USD 50/t-CO_2 for most technologies and regions; novel technologies could help reduce some costs (*high confidence*). The capital cost of a coal or gas electricity generation facilities with CCS is almost double than without CCS (Zhai and Rubin 2016; Rubin et al. 2015; Bui et al. 2018). Additionally, the energy penalty increases the fuel requirement for electricity generation by 13-44% leading to further cost increases (Table 6.2).

Table 6.2 Costs and efficiency parameters of CCS in electric power plants; values extracted from (Muratori et al. 2017a)

	Capital Cost [USD/kW]	Efficiency [%]	CO_2 Capture Cost [USD/ton-CO_2]	CO_2 Avoided Cost [USD/ton-CO_2]
Coal (steam plant) + CCS	5800	28%	63	88
Coal (IGCC) + CCS	6600	32%	61	106
Natural Gas (CC) + CCS	2100	42%	91	33
Oil (CC) + CCS	2600	39%	105	95
Biomass (steam plant) + CCS	7700	18%	72	244
Biomass (IGCC) + CCS	8850	25%	66	242

Other approaches to reduce CCUS costs rely upon utilising the revenues from co-products such as oil, gas or methanol and also clustering of large-point sources to reduce infrastructure costs; the potential for such reduction is limited in due to low sink availability but it could jumpstart initial investments (*medium confidence*). Injecting CO_2 into hydrocarbon formations for enhanced oil or gas recovery produce revenues and lower costs (Edwards and Celia 2018). While enhanced oil recovery potential is <5% of the actual CCUS needs, they can enable early pilot and demonstration projects (Núñez-López and Moskal 2019). CO_2 is effectively stored even when the downstream combustion of oil/gas is considered (Sminchak et al. 2020; Menefee and Ellis 2020). Moreover, geographical circumstances determine the prospects of cost reduction via economies-of-scale. By clustering together of several CO_2 sources, overall costs may be reduced by USD 10/t-CO_2 (Abotalib et al. 2016; Garg et al. 2017a). The major pathways for methanol, methane, liquid fuel production and cement curing have costs greater than USD 500/t-CO_2 (Hepburn et al. 2019). The success of these pathways therefore depends on the value of such fuels. At present, U.S. methane prices are low due to large unconventional gas production, making this pathway cost-prohibitive in the U.S.

Carbon capture, utilisation, and storage technologies are largely unfamiliar to the public (Tcvetkov et al. 2019; L'Orange Seigo et al. 2014) (*high confidence*). People may not have formed stable attitudes and risk perceptions regarding these technologies (Daamen et al. 2006) (*medium confidence*). In general, low support has been reported for CCS technologies (Allen and Chatterton 2013; Demski et al. 2017). When presented with neutral information on CCS, people favor other mitigation options such as renewable energies and energy efficiency improvements (De Best-Waldhober et al. 2009; Scheer et al. 2013; Karlstrøm and Ryghaug 2014). Although few totally reject CCS, specific CCS projects have faced strong local resistance which has contributed to the cancellation of CCS projects (Terwel et al. 2012; L'Orange Seigo et al. 2014). Communities also associate CCU to be lower-risk and view it more favorably than CCS (Arning et al. 2019).

CCUS requires considerable increases in some resources and chemicals, most notably water. Several power plants with CCUS might shutdown periodically due to water scarcity (*high confidence*). Water withdrawals for CCUS are 25-200%, higher than plants with CCUS (Yang et al. 2020; Rosa et al. 2020b). The increase is slightly lower for non-absorption technologies. In regions prone to water scarcity such as Southwestern US or Southeast Asia, this may result in power plant shutdowns during summer months (Liu et al. 2019b; Wang et al. 2019c).

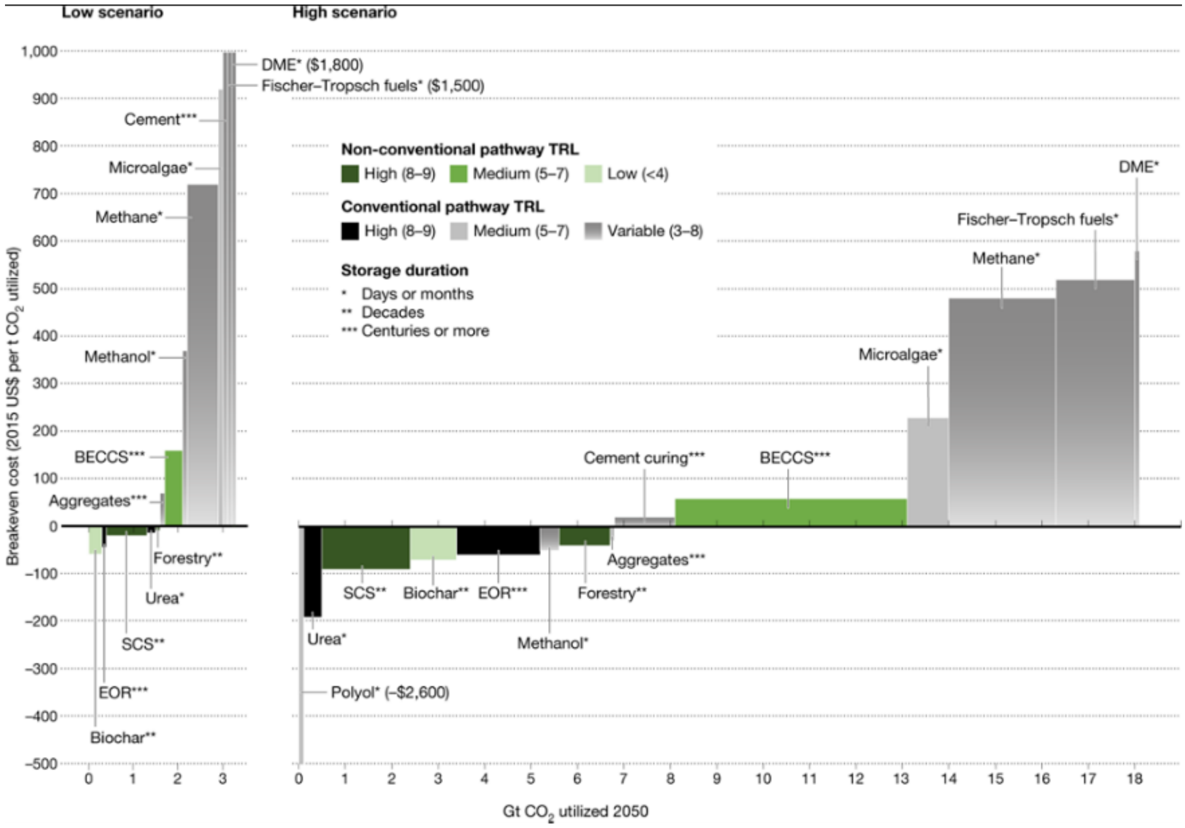


Figure 6.14 Costs and potential for different CO_2 utilisation pathways (Hepburn et al. 2019)

Because CCUS always adds cost, policy instruments are required for its viability (*high confidence*). Relevant policy instruments include financial instruments such as emission certification and trading, legally enforced emission restraints, and carbon pricing (Haszeldine 2016; Kang et al. 2020)The recent US 45Q tax credits offer nationwide tax credits CO_2 capture projects at >USD 35-50/t-CO_2 which might be useful for some efficient plants (Esposito et al. 2019). Similarly, California's low-carbon fuel standard offer benefits to CO_2 capture at some industrial facilities such as biorefineries and refineries (Von Wald et al. 2020)

6.4.2.6 Bioenergy

Bioenergy is potentially a high-value and large-scale mitigation option. It can support many different parts of the energy system, could be particularly valuable for hard-to-decarbonise sectors with limited alternatives to fossil fuels (e.g., aviation, heavy industry), and can be used with CCUS to create negative emissions. The technology for large-scale production of biofuels from second generation processes, however, is not competitive, and growing dedicated bioenergy crops raises a broad set of sustainability concerns. Its long-term role in low-carbon energy systems is therefore uncertain. (*high confidence*)

Assessing the potential for purpose-grown bioenergy is challenging due to its far-reaching linkages to issues beyond the energy sector, including competition with land for food production and forestry, impacts on ecosystem services, and deforestation (*high confidence*) (IPCC 2020; Chapter 12). These factors, rather than geophysical characteristics, largely define the potential for bioenergy and explain the difference in estimates of potential (*high confidence*). Wastes and residues (e.g., agricultural, forestry, animal manure, processing) or biomass grown on degraded, surplus, and marginal land provides opportunities for cost-effective and sustainable bioenergy at significant scale (*low confidence*) (Saha and Eckelman 2018; Fajardy and Mac Dowell 2020).

Bioenergy is extremely versatile: technology pathways exist to produce electricity, liquid fuels, gaseous fuels, including hydrogen, and solid fuels from bioenergy as well as other value-added products; it can also provide a source of CDR through combination with CCUS and through biochar sequestration (*high confidence*). A key feature of bioenergy is the large number of end products that could potentially arise from this currently available feedstock. Different chemical and biological conversion pathways could be utilised based on the feedstock availability and end-use targeted Figure 6.15. While most types of biomass could be converted to electricity, other options are currently more competitive and appealing (6.4.2.1-6.4.2.5). The most notable pathway for electricity production is through gasification incorporating CO_2 capture, especially as it offers an important co-firing route with coal (Hermwille et al. 2019). Both gasification and pyrolysis can deliver hydrogen but gasification is considerably more flexible in terms of the feedstock that could be utilised. While potentially cost-competitive, these pathways are only in the demonstration stage (IEA 2018b; Molino et al. 2018). Sugar-based biofuels have been used in several countries with ethanol blending to gasoline. However, there is a limit to the extent to which this route may be decarbonised because the sources of CO_2 are non-stationary and dispersed. Instead, for future transport fuels, both gasification (through further Fischer-Tropsch processing) and pyrolysis using cellulosic feedstocks are being targeted. Finally, very high moisture wastes such as dairy manure and wastewater sludge can produce renewable natural gas (RNG) when processed through anaerobic digestion. These can then offer direct transition routes for existing natural gas power plants.

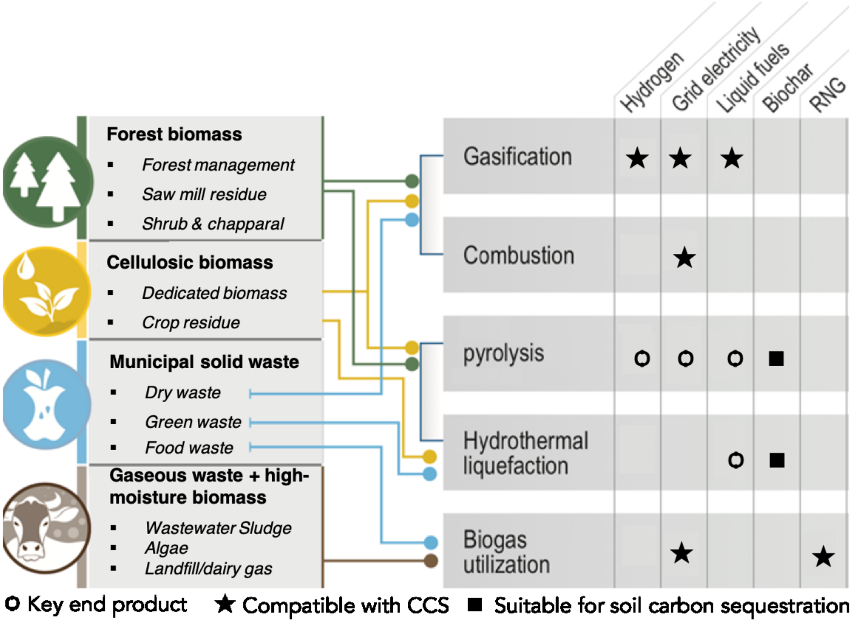


Figure 6.15 Range of bioenergy conversion pathways based on feedstock, targeted end product and compatibility with CDR via CCUS and soil carbon sequestration (Modified from Baker et al, 2020)

A key feature of bioenergy is its ability to deliver CDR. By capturing CO_2 in different parts of the supply chain, some bioenergy routes can produce net-negative GHG emissions in what is called bioenergy with CO_2 capture and storage (BECCS). There exists a high potential for CDR through BECCS (Smith et al. 2016; Fuss et al. 2018), but issues with biomass production will influence the viability of this option. Some early opportunities for low-cost BECCS are being utilised in the ethanol sector but these are applicable only in the near-term at the scale of ≤ 100 Mt-CO_2 yr^{-1} (Sanchez et al. 2018). In the longer-term, gasification and chemical looping on solid biomass present appealing prospects for BECCS and could become cost-competitive with fossil fuels with CCUS around 2035 (Bhave et al. 2017). Additionally, both pyrolysis and hydrothermal liquefaction produce biochar which is 80% permanently sequestered carbon. Apart from delivering CDR, this could deliver additional purposes in the form of soil amendments (Wang et al. 2014b).

While liquid and gaseous fuels from bioenergy could prove highly valuable for deep decarbonisation, ¨second-generation" fuels that could be produced at scale are not currently economically viable and will require substantial breakthroughs to become competitive (*high confidence*). The progress in liquid fuels so far has largely been through ethanol from food crops such as sugarcane or corn, which poses competition to food availability and has lower yield per land area. Developments in 2nd generation fuels, which are produced from non-food, cellulosic feedstocks and offer other ancillary benefits, are still under progress and are at the pilot stage (Müller-Langer et al. 2014; Prussi et al. 2019). These can be critical to decarbonise some applications with limited alternatives, like aviation and industry (Muratori et al. 2017b; Mousa et al. 2016). The underlying processes (such as Fischer-Tropsch) are very sensitive to impurities such as sulfur. Moreover, the produced fuels require considerable upgrading (often 1-20% hydrogen by weight) to reach "drop-in" conditions – that is, conditions in which they may be used directly consistent with current standards (Ostadi et al. 2019; Salman et al. 2020). Similarly, technologies producing natural gas (e.g. digestion) tend to be less efficient than thermochemical approaches and often produce large amounts of CO_2, requiring the produced fuels to undergo significant upgrading (Melara et al. 2020). Scaling-up these processes requires robust business strategies and optimised use of co-products (Lee and Lavoie 2013).

BECCS is not commercially available and several technological and institutional barriers exist for its implementation at large scale – these include large upstream energy requirements in processing and conversion of biomass, lack of biomass sources and CO_2 sinks in proximity in several regions and limited availability of CO_2 capture technologies for high-moisture biomass (*high confidence*). Several dimensions of issues would need to be addressed for widespread BECCS deployment. Detailed life-cycle scrutiny of BECCS indicates a tradeoff between CDR and energy provision with energy rate of investment falling below the commercial threshold of 3:1 (Fajardy and Mac Dowell 2018; Tanzer and Ramírez 2019). The processing requirements (drying, dewatering, pelletising) of different feedstocks is energy-intensive, and when utilising current power plants, the efficiency would be close to 22% with an increase up to 28% with advanced technologies (Zhang et al. 2020). Only limited locations show proximity of biomass sources and high-quality geologic sinks, necessitating additional widespread pipeline infrastructure or means to transport biomass over larger distances, such as through pelletising (Baik et al. 2018b; Singh et al. 2020).

The broader environmental implications of bioenergy production extend beyond direct combustion products that may impact air quality and include land use and land use change emissions, non-CO_2 GHG emissions, water use, fertiliser use, and biodiversity (*high confidence*). Overall environmental impact of bioenergy production at scale remains uncertain and varies by regions and applications (*high confidence*). At scales consistent with energy transitions discussed later in this chapter (Section 6.7), bioenergy is likely to exert very high stress on land use, which might be difficult to reconcile with planetary boundaries (Gerten et al. 2020; Heck et al. 2018 Chapter 12). Alleviating this will require some combination of increasing in crop yields, changes in conversion efficiency of biomass to usable energy forms, and advanced biotechnologies for getting higher fuel yield per tonne of feedstock (Henry et al. 2018). Water use for irrigation could also increase to as high as the need for food crop production for some crops (Stenzel et al. 2019; Gerbens-Leenes 2018). This could be reduced with effective utilisation of residues as bioenergy feedstock. Nitrogen fertiliser use is anticipated to be 150-200% of the present day use in 2°C transitions (Lade et al. 2020; Kato and Yamagata 2014).

Life-cycle climate impacts from bioenergy are subject to large uncertainties – these arise from differences in feedstocks and sourcing, processing requirements for biomass resources, assumptions on sources of other fuels (especially electricity), retention of carbon in the solid or liquid co-products, and methodological and allocation differences in the way waste and dedicated biomass are treated (*high confidence*). Due to the potentially large upstream requirements and associated indirect GHG emissions discussed above, bioenergy systems may fail to deliver near-zero emissions (Staples et al. 2017; Lade et al. 2020). Similarly, the CDR function of BECCS remains uncertain if the upstream burdens are not optimised (Fajardy and Mac Dowell 2017; Tanzer and Ramírez 2019). Associated land use change emissions could also accordingly increase substantially and could potentially jeopardise the low-carbon benefits of bioenergy if high carbon-content ecosystems are used for bioenergy crop cultivation (Harper et al. 2018; Drews et al. 2020). A key part of these life-cycle emissions is also the downstream fate of the co-products produced with the gaseous or liquid fuels. The carbon in the form of the aqueous co-products eventually gets emitted back into the atmosphere upon treatment in wastewater treatment plants while a substantial part of the carbon pool of the solid co-products created is labile (Buss et al. 2019). Accordingly, process conditions (temperature, pressure, catalyst) need to be optimised to produce higher usable fuel. In view of the large differences, effective governance and incentivisation of bioenergy requires clearly defined regulations on how emissions and sequestration are accounted for (Torvanger 2019). Similarly, consistency in approaches is required for allocation of emissions between dedicated and residual biomass feedstock (e.g. ethanol produced from corn grain versus corn ethanol).

The cost of 1st generation, sugar-based bioenergy is currently comparable though on average higher than other forms of final energy (*high confidence*). These costs are very contextually-dependent and regions having large waste resources are already producing low-cost bioenergy (*high confidence*)(Hanssen et al. 2020). In the future, technology costs are anticipated to decrease but energy from purpose-grown, cellulosic feedstocks will likely be expensive, creating uncertainty around bioenergy costs (*medium confidence*). Large-scale deployment of early opportunities especially in the liquid fuel sector may reduce the technological costs associated with biomass conversion(IEA 2020e). At the same time, the cost of feedstock may itself rise as bioenergy requirements increase, especially in scenarios with large BECCS deployment (Daioglou et al. 2020; Muratori et al. 2020).

Table 6.3 The costs of electricity generation, hydrogen production and liquid fuels production from biomass. These costs are adapted by considering the 25-75% CI range from the (Daioglou et al. 2020a)

All values in USD /MWh	Low	Median	High
Bioelectricity with CCS	74	86	113
Bioelectricity without CCS	66	84	112
Biohydrogen with CCS*	42	62	61
Biohydrogen without CCS*	41	46	60
Bioliquids cellulosic with CCS	51	57	81
Bioliquids ethanol without CCS	38	50	66

*** Using cellulosic feedstocks**

The costs are also dependent on the end-use application. For instance, while the cost of bioelectricity is slightly higher than current grid electricity, costs of some biofuels are quite comparable to current fossil fuels, though their scalability is limited.

- Liquid Biofuels. Starch ethanol is largely used in some regions and its cost is currently USD 40-65/MWh, which is comparable to the costs of gasoline. However, supply is limited and for the key technologies compatible with CCS (Fischer-Tropsch and cellulosic ethanol), the costs are higher in most regions (Li et al. 2019). It is projected that technological learning could reduce these costs by half resulting from technological learning (IEA 2020e).

- Hydrogen. The costs of hydrogen production from biomass are somewhat higher than, but comparable to that produced by natural gas reforming with CCS i.e. blue hydrogen. Further, the incremental cost for incorporating CCS here are as low as <5% in some cases since the gasification route creates a high-purity stream of CO_2 (Muratori et al. 2017b; Sunny et al. 2020). While these processes have fewer ongoing prototypes/demonstrations, they are significantly (by 50-200%) cheaper than hydrogen produced from electrolysis utilising solar/wind resources (Kayfeci et al. 2019; Newborough and Cooley 2020).
- Electricity. The costs of baseload electricity production with biomass are higher than corresponding forms of fossil energy production with and without CCS, and are likely to remain as such without carbon pricing (Bhave et al. 2017). The additional costs of CO_2 capture are high using conventional solvent based technologies. However, upcoming technologies such as chemical looping are well-suited to biomass and create low-cost BECCS opportunities.

Acceptability of biomass and biofuel is relatively low compared to other renewable low-carbon fuels like solar and wind (Poortinga et al. 2013; EPCC 2017; Peterson et al. 2015; Ma et al. 2015) and comparable to natural gas (Scheer et al. 2013) (*medium confidence*). Yet, people know relatively little about biomass compared to other energy sources (Whitmarsh et al. 2011a; EPCC 2017). People tend to have more clear views on biofuels compared to other mitigation options (Allen and Chatterton 2013; Allen and Chatterton 2013). People evaluate biomass from waste products (e.g. food waste) more favorably than grown-for-purpose energy crops, which are more controversial (Demski et al. 2015; Plate et al. 2010). The most important concerns about woody biomass are air pollution and loss of local forests (Plate et al. 2010). Various types of bioenergy additionally raise concerns about landscape impacts (Whitmarsh et al. 2011a). Moreover, many people do not see biomass as a renewable energy source, possibly because it involves burning of material.

Based on the large and potentially unprecedented uncertainties due to regional circumstances, scale, trade, and linkages to land and food systems, bioenergy requires clear regulations to reconcile with planetary boundaries (*high confidence*). Large scale international trade of biomass might be required to support a global bioeconomy, raising questions about infrastructure, logistics, financing options, and global standards for bioenergy production and trade Current biomass trade exceeds 1 EJ globally but will need to expand considerably if bioenergy will play a large role in climate change mitigation (Proskurina et al. 2019a). Future biomass trade routes may evolve very differently than today's routes (Daioglou et al. 2020b). Accordingly, necessary regulations for international trade and remuneration schemes would need to be developed. Additional institutional and economic barriers are associated with accounting of negative emissions and BECCS (Fuss et al. 2014; Muratori et al. 2016; Fridahl and Lehtveer 2018). A full-scale bioenergy sector might lead to employment of workers displaced from the decline in use of fossil energy and increase in farm incomes (Section 6.7.7). Several of these workers might be in the unskilled labor segment and may help counter job losses in the fossil fuel industry.

6.4.2.7 Fossil Energy

Fossil fuels play a unique role in climate change mitigation. On the one hand, the primary mechanism for reducing emissions is to eliminate the unabated use of fossil fuels. On the other hand, fossil energy combined with CCUS provides a means to produce low- or near-zero carbon energy while utilising the available base of fossil energy worldwide and limiting stranded assets. While Section 6.4.2.5 discusses the important aspects of CCUS with fossil fuels, this section aims to elucidate the feasibility criteria around these fuels itself.

The resource base of fossil fuels has continued to rise as a result of advanced exploration and utilisation techniques (*high confidence*). A fraction of these available resources can be used consistent with mitigation goals when paired with storage and utilisation opportunities in close geographical proximity (*high confidence*). Based on continued exploration, the fossil fuel resource base of countries has increase significantly, e.g. an increase in 9% for gas reserves and 12% for oil reserves was observed in the U.S. between 2017 and 2018. This is a result of advanced exploration techniques which are often subsidised (Lazarus and van Asselt 2018; MA et al. 2018). Fossil resources are distributed unevenly throughout the globe depicting large geographical heterogeneity. Coal represents the largest remaining resource (close to 500,000 EJ). Oil and gas resources are an order of magnitude smaller (15-20 EJ each). Significant impacts of unconventional fossil fuels have been seen in the last decade through technological development globally. Discovered ultimate recoverable resources of both unconventional oil and gas are comparable to conventional oil and gas (Court and Fizaine 2017). That said, around 80% of coal, 50% of gas and 20% oil are likely to remain unextractable under 2°C constraints (McGlade and Ekins 2015a; Pellegrini et al. 2020). This indicates that it is unlikely that there will be a natural phaseout of these fuels owing to a lack of reserves and instead such a phase-out would need to be planned. The key consideration in which resources would be utilised would likely be determined to the extent to which they could be paired up with CCUS resource-base. Availability of CCUS technology not only allows continued increase of fossil fuel use as a capital resource for countries but also paves the way for CDR through BECCS, resulting in greater flexibility on mitigation (Pye et al. 2020; Haszeldine 2016). Reiterating from Section 6.4.2.5, while the amount of theoretical geologic sequestration potential is vast, there are limits on how much resource base could be utilised based on geologic, engineering and source-sink mapping criteria (Budinis et al. 2017).

Technological changes have continued to drive down the costs of extracting fossil fuels. There is also an outlook on the diversification of fossil fuels, most notably via the hydrogen market (high evidence). The costs of extracting oil and gas globally have gone down by utilising hydraulic fracturing and directional drilling for resources in unconventional reservoirs (Wachtmeister and Höök 2020). While the extraction of these resources is still more expensive than those derived from conventional reservoirs, the large availability has significantly reduced global prices. The emergence of liquefied natural gas (LNG) markets has also provided an opportunity for export of natural gas to significantly farther distances from the place of production (Avraam et al. 2020). The increase in availability has been accompanied by an increase in the production of natural gas liquids, as a co-product to oil and gas. During 2014-2019, the exports of these liquids increased 160%. These liquids can present a lower-carbon alternative to liquid fuels and hydrocarbons with appropriate process upgradation (Lee and Elgowainy 2018; Dutta et al. 2019). Finally, on the demand side, natural gas can be converted to hydrogen using steam methane reforming, which is a technologically mature process. When combined with 90% CO_2 capture, the costs of this process are considerably less than hydrogen production via electrolysis and ranges around USD 1.5-2/kg-H_2 (Newborough and Cooley 2020; Collodi et al. 2017).

In terms of coal resources, significant potential exists for gasifying deep-seated coal deposits *in situ* to produce hydrogen. Doing so reduces large fugitive methane emissions from underground coal mining. The integration costs of this process with CCUS are less than with natural gas reforming (Verma and Kumar 2015). Similarly, for ongoing underground mining projects, coal mine methane recovery shows a positive outlook for major coal producers such as China and India. This technology can reduce the fugitive methane emissions by 50-75% (Zhou et al. 2016; Singh and Sahu 2018).

The cost of producing electricity has remained roughly the same with some regional exceptions while the costs of transport fuels has gone down significantly (*high confidence*). The cost of producing electricity from fossil fuels has largely remained static, barring few regional changes, e.g. 40% reduced costs in the U.S. for natural gas (Rai et al. 2019). The gas wellhead price has declined by almost 2/3rd due to vast abundance of gas. Similarly, the global price of crude oil has declined from almost USD 100/bbl to USD 55/bbl in the last five years. These have largely been triggered through unconventional oil and gas availability through the breakthrough in hydraulic fracturing and horizontal drilling, specifically in North America (IEA 2020f). Another parameter which could be inferred as a cost of fossil fuel extraction is the energy return of investment (EROI). Fossil fuels create significantly larger amounts of energy per unit energy invested – or in other words have much larger EROI than most cleaner fuels such as biomass, where intensive processing reduces EROI (Hall et al. 2014). That said, recent years have seen a decrease in EROI, especially as more underground coal mining has continued in China. Exploitation of large unconventional gas reservoirs is also energy intensive which leads to reduction in EROI. The primary energy EROI of fossil fuels has converged at about 30, which represents a 20-point decrease from the 1995 value for coal (Brockway et al. 2019).

Several countries have large reserves of fossil fuels, which is considered as significant capital. Owing to climate constraints, these may become stranded causing considerable economic impacts (*high confidence*). While global fossil energy resources are resources are greater than 500,000 EJ, more than half of these resources would likely be unburnable even in the presence of CCUS (Pye et al. 2020; McGlade and Ekins 2015a). This would entail a significant capital loss for the countries with large reserves. The total amount of stranded assets in such a case would amount to USD 1-5 trillion (Box 6.11).

Apart from the large CO_2 emissions and air pollutants from fossil fuel combustion (reported in AR5), other environmental impacts include fugitive methane leakages and implications to water systems**.** While the rate of methane leakage from unconventional gas systems is uncertain, their overall GHG impact is less than coal (Deetjen and Azevedo 2020; Tanaka et al. 2019). The stated rate of leakage in such systems ranges from 1-8% and reconciling them requires a combination of top-down and bottom-up approaches (Grubert and Brandt 2019; Zavala-Araiza et al. 2015). Similarly, for coal mining, the fugitive methane emissions have grown despite some regulations on the degree to which emission controls must be deployed. Recent IPCC inventory guidance also notes considerable CO_2 emissions resulting from spontaneous combustion of the coal surface and accounting for these emissions will likely increase the overall life-cycle emissions by 1-5% (Fiehn et al. 2020; Singh 2019; IPCC 2019).

Another key issue consistently noted with unconventional wells (both oil and gas, and coalbed methane) is the large amount of water requirements. The overall water footprint of unconventional reservoirs is higher than conventional reservoirs because of higher lateral length and fracturing requirements (Scanlon et al. 2017; Kondash et al. 2018). Moreover, produced water from such formations is moderately to highly brackish, and treating such waters has large energy consumption (Singh and Colosi 2019; Bartholomew and Mauter 2016).

Oil and coal consistently rank among the least preferred energy sources in many countries. The main perceived advantage of fossil energy is the relative low costs, and emphasising these costs might increase acceptability somewhat (European Social Survey 2018; Hazboun and Boudet 2020; Boyd et al. 2019) (*high confidence*). Their average acceptability is similar to acceptability of nuclear energy, although evaluations are less polarised. People evaluate natural gas as somewhat more acceptable. Yet, natural gas is evaluated as less acceptable than renewable energy sources, although evaluations of natural gas and biogas are rather similar (Liebe and Dobers 2019; Plum et al. 2019). Acceptability of fossil energy tends to be higher in countries and regions that strongly rely on them for their energy production (Boyd et al. 2019; European Social Survey 2018).Yet, combining fossil fuels with CCS can increase their acceptability (Van Rijnsoever et al. 2015; Bessette and Arvai 2018). Some people seem ambivalent to natural gas, meaning that they perceive benefits (e.g., affordability, less carbon emissions than coal) and disadvantages (e.g., finite resource, contributing to climate change) at the same time (Blumer et al. 2018).

Fossil fuel subsidies have been valued of the order of USD 0.5-5 trillion annually by various estimates which have the tendency to introduce economic inefficiency within systems (Merrill et al. 2015; Jakob et al. 2015) (*high confidence*). Subsequent reforms have been suggested by different researchers who have estimated reductions in CO_2 emissions may take place if these subsidies are removed (Mundaca 2017). Such reforms could create the necessary framework for enhanced investments in social welfare – through sanitation, water, clean energy – with differentiating impacts (Edenhofer 2015).

6.4.2.8 Geothermal Energy

The geophysical potential of geothermal resources is 10 to 100 times the current generation (*medium confidence*). Geothermal energy can be used directly for various thermal applications, including space heating and industrial heat input, or converted to electricity (Moya et al. 2018; REN21 2019; Limberger et al. 2018). Suitable aquifers underlay 16% of the Earth's land surface and store an estimated $4 \cdot 10^5$to $5 \cdot 10^6$EJ that could theoretically be used for direct heat applications. For electricity generation, the technical potential of geothermal energy is estimated to be between 120 EJ yr^{-1} (to 3 km depth) and 1,100 EJ yr^{-1} (to 10 km depth). For direct thermal uses, the technical potential is estimated to range from 10 to 312 EJ yr^{-1} (IPCC 2011). There is an enormous potential for direct geothermal heat from aquifers, yet only 0.15% of the annual global final energy consumption is supplied by geothermal direct heat. The mismatch between potential and developed geothermal resources is caused by high up-front costs, decentralised geothermal heat production, lack of uniformity among geothermal projects, geological uncertainties, and geotechnical risks (Limberger et al. 2018).

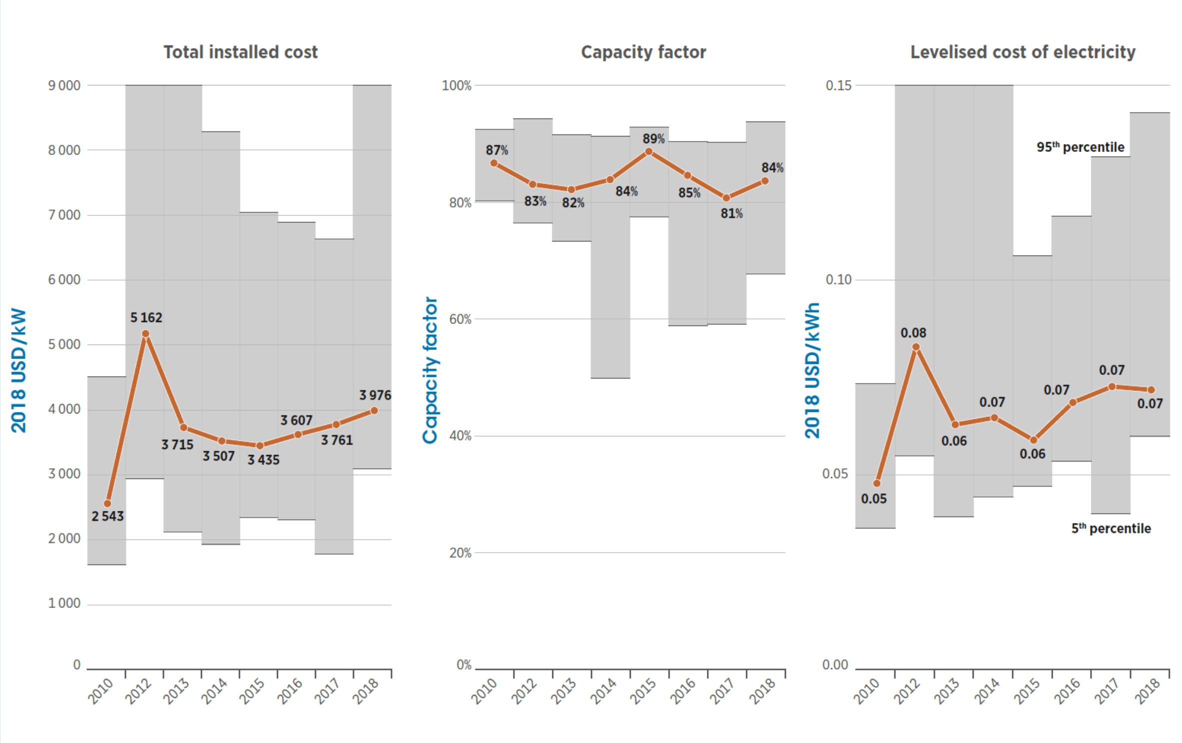


Figure 6.16 Global weighted average total installed costs, capacity factors and LCOE for geothermal power, 2010

Source (IRENA, 2018)

Geothermal energy is heat that is stored in the subsurface and is a renewable resource that can be sustainably exploited. There are two main types of geothermal resources: convective hydrothermal resources, where the Earth's heat is carried by natural hot water or steam to the surface; and hot dry rock resources, where there is no possibility of extraction using water or steam, and other methods must be developed. There are three basic types of geothermal power plants: (1) dry steam plants use steam directly from a geothermal reservoir to turn generator turbines; (2) flash steam plants take high-pressure hot water from deep inside the Earth and convert it to steam to drive generator turbines; and (3) binary cycle power plants transfer the heat from geothermal hot water to another liquid. Many of the power plants in operation today are dry steam plants or flash plants (single, double and triple) harnessing temperatures of more than 180°C. However, medium temperature fields are more and more used for electricity generation or for combined heat and power thanks to the development of binary cycle technology, in which geothermal fluid is used via heat exchangers to heat a process fluid in a closed loop. Additionally, new technologies are being developed like Enhanced Geothermal Systems (EGS), which are in the demonstration stage (IRENA 2018). Technologies for direct uses like district heating, geothermal heat pumps, greenhouses, and for other applications are widely used and can be considered mature. Given the limited number of plants commissioned, economic indicators (Figure 6.16) depend heavily on site characteristics.

Geothermal has several adverse environmental impacts, including air pollution, noise pollution, water pollution, land and water use, land subsidence, thermal pollution, aesthetics, and other catastrophic events such as seismic events (*high confidence*).

Public awareness and knowledge of geothermal energy is rather low. Geothermal energy is evaluated as less acceptable than other renewable energy sources like solar and wind, but is preferred over fossil and nuclear energy, and in some studies, over hydroelectric energy (Karytsas et al. 2019; Pellizzone et al. 2015; Steel et al. 2015; Hazboun and Boudet 2020) (*high confidence*). Some people worry about installment of geothermal energy production near one's home, similar to worry over solar and wind projects (Pellizzone et al. 2015). The most important concerns about geothermal energy involve water usage, water scarcity, and seismic risks of drilling activities (Dowd et al. 2011). Moreover, noise, smell and damages to the landscape have been reasons for protests against specific projects (Walker 1995). At the same time, people perceive geothermal energy as relatively environmentally friendly (Tampakis et al. 2013).

6.4.2.9 Marine Energy

The oceans are a vast source of energy (Hoegh-Guldberg et al. 2019) and an emerging alternative to fossil fuels, which comprises energy extraction from tides, waves, ocean thermal gradients, currents and salinity gradients (Bindoff et al. 2019). Tidal energy, which uses elevation differences between high and low tides, appears in two forms: potential energy (rise and fall of the tide) and current energy (from tidal currents). The global technically harvestable tidal power from areas close to the coast is estimated as nearly 1 TW (Kempener and Neumann 2014a). The potential for tidal current is estimated to be larger than that for tidal range or barrage (Melikoglu 2018). Ocean wave is abundant and predictable energy and can be extracted directly from surface waves or from pressure fluctuations below the surface (Melikoglu 2018). Its technical potential is estimated between 2,000–4,000 TWh/year (Kempener and Neumann 2014b). The temperature gradients in the ocean can be exploited to produce energy, and its total estimated available resource could be up to 30 TW (Kempener and Neumann 2014c). Salinity gradient energy is also known as osmotic power, and the global technical and theoretical salinity gradient potentials could be over 5,000 TWh/year (Kempener and Neumann 2014d). The greatest advantage of marine energy is that their sources are highly regular and predictable, and energy can be furthermore generated both day and night. The greatest barrier to most marine technology advances is the relatively high upfront costs, uncertainty on environmental regulation and impact, need for investments and insufficient infrastructure (Kempener and Neumann 2014b,a).

6.4.2.10 Waste-to-Energy

Waste-to-energy describes technologies that convert waste (organic and inorganic fraction) into energy such as heat, fuel, and electricity. Thermal (incineration, gasification, and pyrolysis) and biological (anaerobic digestion and landfill gas to energy) technologies are commonly used (Ahmad et al. 2020). Waste-to-energy technologies contribute to climate mitigatHion via clean electricity production and reduction of GHG emissions that would have been emitted from landfills and fossil fuel power plants.

Waste-to-energy technologies can reduce the volume of waste whiles producing sustainable energy to meet the current demand. Waste-to-energy sector could potentially provide about 13 GW of electricity globally (Kumar and Samadder 2017). Incineration plants can reduce the mass (70%-80%) and volume (80-90%) of waste (Haraguchi et al. 2019). Waste-to-energy plants have a positive environmental impact and the ability to reduce GHG emissions. For every ton of waste treated by waste-to-energy plants, 1 ton of GHG is avoided (Clean Earth 2020). The by-product of the anaerobic digestion process could be used as a nutrient-rich fertiliser for enhancing soil richness for agricultural purposes (Wainaina et al. 2020). Incineration technology can minimise water and soil pollution (Gu et al. 2019). However, if not correctly handled, dust, and gases such as SO_2, HCI, HF, NO_2, and dioxins in the flue gases can harm the environment (Dieter Mutz Christoph Hugi, Thomas Gross 2017).

Waste-to-energy is an expensive process compared to other energy sources such as fossil fuels and natural gas (Mohammadi and Harjunkoski 2020). However, the environmental and economic benefits make its high financial costs justifiable. The total revenue generated from the global waste-to-energy market in 2015 was USD 25 billion, and it is predicted to increase in the coming years. The rise in the revenue results from the high demand for biological technology (Grand View Research 2016). Waste-to-energy technologies should be advanced with state-of-the-art pollution control devices (Grand View Research 2016).

6.4.3 Systems and System Integration

GHG emissions are emitted across the economy. This implies that cost-effective decarbonisation requires a “system of systems” approach in which different sectors are fully integrated. Research indicates that flexibility technologies and advanced control of integrated energy systems – for example, infrastructures of electricity, heating/cooling, gas/hydrogen, transport sectors – could reduce energy investment and network infrastructure investments by more than 20% in low-carbon energy systems (Strbac et al. 2015; Zhang et al. 2019).

The electricity grid will serve as a backbone of future low-carbon energy systems, including a transition to digitalisation-based control paradigm (Strbac et al. 2018; Münster et al. 2020). An important challenge will be to integrate large amounts of variable renewable electricity technologies (Hansen et al. 2019), particularly wind and solar generation (Perez et al. 2019; Bistline et al. 2019). This will present a challenge because the balance between demand supply needs to be maintained at timescales from annual and seasonal to sub-seconds. Increased renewable shares, which are inverter-based, will reduce system inertia (Malekpour et al. 2020), requiring greater frequency regulation, particularly to deal with sudden losses of supply, for example, as a result of a failure of a large generator or interconnector or a rapid increase in demand (Teng et al. 2017; Chamorro et al. 2020). Another challenge is that variable renewable generation will displace the energy produced by conventional fossil-fueled plants, but its ability to displace the capacity of fossil generation will be limited in the absence of sufficient flexibility technologies such as energy storage (Strbac et al. 2015a). Furthermore, the electrification of segments of the heat and transport sectors represents a major challenge as the increase in peak demand would be disproportionally higher than the corresponding increase in energy. Surges in peak demand may require significant reinforcement of generation and network infrastructures if the historical passive system operation paradigm is maintained (Strbac and Aunedi 2016).

6.4.3.1 Importance of cross-sector coupling for cost effective energy system decarbonisation

Integrated whole-system approaches will be critical to minimise the cost of transitions to net-zero energy systems (*high confidence*). The lack of flexibility in the current electricity system fundamentally limits high penetration of variable renewable electricity, as well as relatively inflexible nuclear power. At the same time, the huge latent flexibility hidden in other energy sectors – for example, heating and cooling, hydrogen, transport, and gas systems – provides opportunities to take advantage of synergies and coordinate across energy sectors (Clegg and Mancarella 2018; Ceseña and Mancarella 2019, Zhang et al. 2018).

Different energy services can be supplied by different energy carriers, including electricity, gases such as hydrogen, and thermal energy (Figure 6.17). A cost-effective, multi-system paradigm, requires coordination of these systems (European Parliament 2019).

In electricity, sector coupling can significantly increase system flexibility, driven by the interaction between sectors and the application of advanced technologies (Bogdanov et al. 2019; Asfaw et al. 2018; Clegg and Mancarella 2016; Zhang et al. 2019; Heinen et al. 2016). For example, cooling systems and electrified heating systems in buildings can provide flexibility through preheating and precooling via thermal energy storage (Figure 6.17) (Li et al. 2016; Li et al. 2016), reducing system operating costs, carbon emissions, and energy system infrastructure capacity requirements. System balancing services can be provided by electricity storage and electric vehicles based on vehicle-to-grid concepts – through smart control of EV batteries without compromising customers' requirement for transport (Aunedi et al. 2017; Aunedi and Strbac 2020). Hydrogen production processes (power-to-gas and vice versa) and hydrogen storage can support short-term and long-term balancing in the electricity system (Stephen and Pierluigi 2016; Strbac et al. 2018). Electrolysis-based production of hydrogen can increase the resilience of electricity systems with high penetration of variable renewable electricity with the support of hydrogen power plants and long-duration hydrogen storage (Strbac et al. 2018). Hybrid heat pumps can provide flexibility to both electricity and gas systems, by switching optimally to heat pumps in off-peak hours and gas boilers in peak hours (Element Energy 2017; Klein et al. 2014; Dengiz et al. 2019; Fischer et al. 2016). Electricity and gas can be exchanged between countries.

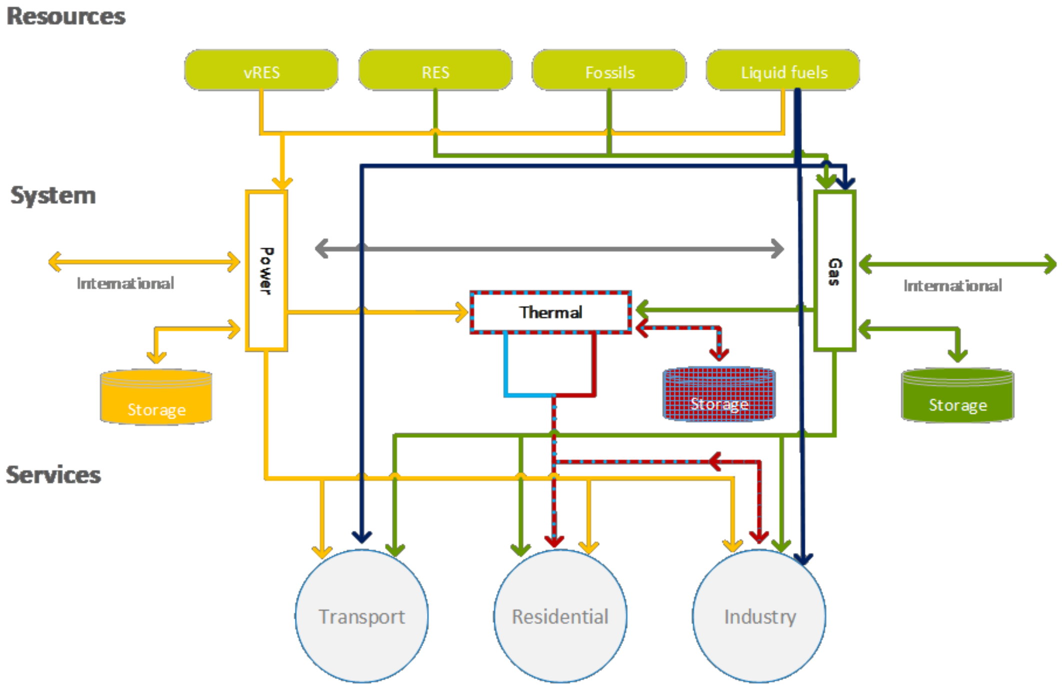


Figure 6.17 Interaction between different energy sectors (power, gas/hydrogen, thermal), showing basic energy sources at the top, different production technologies, various forms of energy storage (electricity, thermal, gas/hydrogen) and transport technologies, in the middle, and end-use energy demand, at the bottom (extracted from (Münster et al. 2020)

Strategic energy system planning – rather than incremental planning – will minimise long-term mitigation costs (*high confidence*). With the whole-system perspective, integrated planning can be optimised by considering both short-term operation and long-term investment decisions, covering infrastructure from local to national and international, while meeting security of supply requirements and taking into account the flexibility provided by different technologies and advanced control strategies (Zhang et al. 2018a; O'Malley et al. 2020a; (Strbac et al. 2020). Research has demonstrated that management of conflicts and synergies between local district and national level objectives, including strategic investment in local hydrogen and heat infrastructure, would drive significant whole-system cost savings (Aunedi et al. 2016; Strbac et al. 2018; Zhang et al. 2018a; Zhang et al. 2019; (Fu et al. 2020). In the context of large-scale offshore wind deployment, long-term planning of the offshore grid infrastructure, including interconnection between different countries and regions, will be provide significant savings when compared to a short-term incremental approach in which every offshore wind farm is individually connected to the onshore grid (Strbac et al. 2014).

6.4.3.2 Role and value of flexibility technologies and advanced control systems

Flexibility technologies – including energy storage, demand side response, flexible generation, grid forming convertors, interconnection – and advanced control systems will enable cost effective and secure mitigation in integrated energy systems (*high confidence*). A number of flexibility resource options are available, including highly flexible thermal generation, grid forming convertors, energy storage, demand-side response and cross-border interconnection to other systems. These technologies have already been implemented, but there is scope for further enhancement. Due to their interdependencies and similarities, there can be both synergies and conflicts for utilising these flexibility options. It will therefore be important to coordinate and optimise the deployment of the potential flexibility technologies and smart control strategies.

- *Flexible generation*. Advances in conventional generation technologies are allowing them to enhance system flexibility. The can start more quickly, operate at lower levels of power output (minimum stable generation), maker faster output change. All of these enable them to more cost-effectively integrate variable renewable electricity.
- *Grid-forming converters.* The ongoing transition of power systems from conventional generation, applying mainly synchronous machines, to inverter-dominated generation is leading to significant operating challenges, mainly associated with reduced system strength, synchronous inertia, and black start capability. Grid-forming converters will be a cornerstone of future power systems dominated by renewable generation. They will address critical stability challenges, including the lack of system inertia, frequency and voltage regulation, and black-start services, while reducing or eliminating the need to operate conventional generation (Tayyebi et al. 2019).
- *Interconnection*. Electricity interconnectors between different regions can facilitate more cost-effective renewable electricity deployment, enabling large-scale sharing of energy, provision of balancing services, and back-up resources, Beyond electricity, energy carriers such as ammonia can also be shared through gas/ammonia/hydrogen based interconnections, strengthening temporal coupling of multi-energy sectors in different regions (Section 6.4.5).
- *Demand Side Response.* Demand-side schemes – including, for example, smart appliances, electric vehicles, thermal energy storage – can potentially provide different types of flexibility services across multiple time frames and system sectors. Furthermore. smart control of end demand, through differentiation between essential and non-essential demand during emergency conditions following outages and/or failures of infrastructure assets, could significantly enhance the resilience of future digitalised low carbon energy systems (Chaffey 2016).
- *Energy storage*. Energy storage technologies (Section 6.4.4) have the ability to act as both demand and generation sources. They can provide services such as system balancing, various ancillary services, and network management. Furthermore, utilisation of renewable energy sources could be enhanced significantly through the use of long-duration energy storage, while reducing the need for firm low-carbon generation.

6.4.3.3 Benefits of digitalisation and advanced control systems

A digitalised energy system operation paradigm, including application of blockchain type technologies, will significantly reduce energy infrastructure investments while enhancing supply security and resilience (*high confidence*). Significant progress has been made in the development of technologies that are essential for transition to digitalised energy control paradigm, although the full implementation in control centers is still under development.

Electrification and the increased integration of the electricity system with other systems will fundamentally transform the operational and planning paradigm of future energy infrastructure. A fully-intelligent and sophisticated coordination of the multiple systems through digitalisation and smart control will be required to support this paradigm shift. This will provide significant savings through optimal utilisation of existing infrastructure at both local, regional, and national levels. It will also facilitate radical changes in the security of supply through redundancy in assets – the traditional approach – to a smart control paradigm, given the rapid development of advanced control systems and communication technologies. Supply system reliability will be enhanced through advanced control of local infrastructure (Strbac et al. 2015b).

Advanced data-driven control of energy system operations will require progressive information and communication technologies and infrastructure, including the internet, wireless networks, computers, software, middleware and dedicated technological developments. This will raise standardisation and cybersecurity issues. Due to the expansion of distributed renewable energy resources, peer-to-peer energy trading is expected to be one of the key elements of next-generation power systems. This will provide a number of benefits, including the creation of a competitive energy market, reduced supply interruptions, and an increase in overall power system efficiency. Blockchain-based technologies could facilitate a shift to decentralised energy system control and support public energy trading without sacrificing users' privacy. This technology, when deployed with smart contracts, is suitable for systems involving many participants, where a prerequisite is digitalisation (e.g., smart meters) (Teufel et al. 2019; Juhar and Khaled 2018).

6.4.3.4 System benefits of flexibility technologies and smart control

New sources of flexibility and advanced control systems provide a major opportunity to reduce low-carbon energy system costs by enhancing operating efficiency and reducing energy infrastructure and low-carbon generation investments, while continuing to meet security requirements (*high confidence).* Key means for creating savings are associated with the following:

- *Efficient operation of energy system*. Flexibility technologies such as storage, demand-side responses, interconnection, and cross-system control will enable more efficient, real-time, demand and supply balancing. This has historically been provided by conventional fossil-fuel generation (Nuytten et al. 2013).
- *Savings in investment in low carbon generation capacity*. System flexibility sources can absorb or export surplus electricity, thus avoiding energy curtailment and associated costs and reducing the need for firm low-carbon capacity from sources such as nuclear and fossil-fuel plants with CCUS (Newbery et al. 2013, Strbac et al. 2015a). For example, analysis has demonstrated that flexibility technologies and advanced control systems could enable the UK's low-carbon emission targets by building 14 GW less nuclear or 20 GW less offshore wind generation. Similarly, DAC be used to sequester carbon using excess variable renewable generation, reducing the need for firm low-carbon generation sources and allowing some residual emissions in electricity or other parts of the energy system.
- *Reduced need for back-up capacity*. System flexibility can reduce system peaks, which can reduce the required generation capacity, particularly peaking plant capacity, with no compromise in energy supply security. This can produce significant savings in investment in conventional generation while meeting supply security standards (Strbac et al., 2020).
- *Deferral or avoidance of electricity network reinforcement/addition*. Flexibility technologies supported by advanced control systems can provide significant savings in investment in electricity network reinforcement that might emerge from increased demand (e.g. driven by electrification of transport and heat sectors). Historical network planning and operation standards are being revised considering alternative flexibility technologies, which would

further support cost-effective integration of decarbonised transport and heat sectors (Vivid Economics 2019).

6.4.4 Energy Storage for Low-Carbon Grids

Energy storage technologies will make low-carbon energy systems more cost-effective, allowing more expensive firm low carbon generation technologies to be replaced with variable renewables (Lever et al. 2016) and reducing investment costs in back-up generation, interconnection, transmission. and distribution network upgrades (*high confidence*). Energy system decarbonisation relies on increased electrification (Section 6.6.2.3). Meeting increasing demands with fluctuating renewable sources presents challenges and could lead to costly infrastructure reinforcements. Energy storage enables electricity from variable renewables to be matched against evolving demands across both time and space, using short-, medium- and long-term storage of excess energy for delivery at a later time or different location.

Table 6.4 Suitability of low carbon energy storage technologies, in terms of the grid services they can provide, as well as overall features such as technology maturity, where Low represents an emerging technology; Med represents a maturing technology and High a fully mature technology. The opportunity for the cost of a technology to reduce over the next decade is represented by Low, Med and High and the lifetime of installations by Long, for projects lasting more than 25 years, Med for those lasting 15-25 years and Short for those lasting less than 15 years. (PSH - Pumped Storage Hydropower (IRENA 2017, Barbour et al. 2016); CAES - Compressed Air Energy Storage (Brandon et al. 2015, IRENA 2017, Luo et al. 2014; LAES - Liquid Air Energy Storage (Luo et al. 2014 , Highview 2019); TES - Thermal Energy Storage (Brandon et al. 2015,Smallbone et al. 2017, Gallo et al. 2016; FES - Flywheel Energy Storage (Yulong et al. 2017, IRENA 2017); LiB – Lithium ion Batteries (IRENA 2017, Hammond and Hazeldine 2015, Staffell, I. and Rustomji, M. et al. 2016, Schmidt et al. 2017c,Nykvist and Nilsson 2015,May et al. 2018, IRENA 2015b; Scap – Supercapacitors (Brandon et al. 2015, Gur 2018) ; RFB - Redox Flow Batteries (IRENA 2017); RHFC - Reversible Hydrogen Fuel Cells (Gur 2018, IEA 2015); PtX – Power to fuels).

Suitability factor	PSH	CAES	LAES	TES	FES	LiB	Scap	RFB	PtX	RHFC
Upgrade deferral	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Energy Arbitrage	✓	✓	✓	✓		✓		✓	✓	✓
Capacity firming	✓	✓	✓	✓	✓	✓		✓	✓	✓
Seasonal storage				✓					✓	✓
Enhanced frequency response					✓	✓	✓	✓	✓	✓
Frequency regulation	✓	✓	✓		✓	✓	✓	✓	✓	✓
Voltage support	✓	✓	✓		✓	✓	✓	✓	✓	✓
Black start	✓	✓	✓			✓		✓	✓	✓
Short term reserve	✓	✓	✓			✓		✓	✓	✓
Fast reserve	✓	✓	✓		✓	✓		✓	✓	✓
Islanding		✓	✓	✓		✓		✓	✓	✓
Uninterruptible power supply					✓	✓	✓	✓		✓
Maturity	High	High	Med	Low	High	Med	Low	Low	Low	Low
Opportunity to reduce costs	Low	Low	Low	Med	Med	High	High	High	Med	High
Lifetime	Long	Long	Long	Long	Med	Short	Med	Med	Med	Short
Roundtrip Efficiency	60-70%	30-60%	55-90%	70-80%	90%	>95%	>95 %	80-90%	35%-60%	<30%

Energy storage technologies can provide a range of different grid services (Table 6.4). Energy storage enhances security of supply by providing real time system regulation services (voltage support, frequency regulation, fast reserve and short-term reserve). A greater proportion of renewable sources reduces system inertia, requiring more urgent responses to changes in system frequency, which rapid response storage technologies are able to provide (enhanced frequency regulation requires responses within subsecond timescale, and frequency regulation involving timescale from seconds to tens of minutes). Investment costs in back-up generation, interconnection, transmission, and distribution network upgrades can thus be reduced (upgrade deferral), meaning that less low carbon generation will need to be built, while still meeting the carbon target. In the event of an outage, energy storage reserves can keep critical services running (islanding) and restart the grid (black start).

No single EST can provide all of required grid services – a portfolio of complementary technologies working together can provide the optimum solution (*high confidence*). Different energy storage technologies can provide these services and support cost-effective energy system decarbonisation (Lever et al. 2016). To achieve very low carbon systems, significant volumes of storage will be required (Strbac et al. 2015a; Section 6.4.3.2). There are few mature global supply chains for many of the less-developed energy storage technologies. This means that although costs today may be relatively high, there are significant opportunities for future cost reductions, both through technology innovation and through manufacturing scale.

Energy storage extends beyond electricity storage and incudes technologies which can store energy as heat, cold, and both liquid and gaseous fuels. Energy storage is a conversion technology, enabling energy to be converted from one form to another. This diversification improves the overall resilience of energy systems, with each system being able to cover supply shortfalls in the others. For example, storage can support the electrification of heating or cooling, as well as transport through electric vehicles, powered by batteries or by fuel cells. Through smart charging schemes and the ability to flow electricity back to the grid (e.g. through vehicle-to-grid), storage significantly reduces the need for costly reinforcement of local distribution networks. By capturing otherwise wasted energy streams, such as heat or cold, energy storage improves the efficiency of many systems, for example, in buildings, data centers and industrial processes.

6.4.4.1 Energy Storage Technologies

Pumped and Storage Hydropower (PSH). PSH makes use of gravitational potential energy, using water as the medium. Off-peak electricity is used to pump water into an elevated reservoir, where it is stored water for later release, when electricity is needed. Hydropower plants incorporating an element of storage, either through seasonal reservoirs or by using off-peak electricity to pump water, have been in use for decades and account for 97% of worldwide electricity storage capacity (IEA 2018c). PSH is best suited to balancing energy needs at a large scale, but conventional PSH plants are not able to provide services requiring a very rapid response and provide power regulation only during generation, not during pumping. The construction itself can cause disruption to the local community and environment, the initial investment is costly and extended construction periods delay return on investment (Section 6.4.2.3).

Advanced pump-turbines are being developed, allowing both reversible and variable-speed operation, finer frequency control and improved round-trip efficiencies (Ardizzon et al. 2014). New possibilities are being explored for small-scale PSH installations and expanding the potential for siting (Kougias et al. 2019). For example, in underwater PSH, the upper reservoir is the sea and the lower is a hollow deposit at the seabed. Seawater is pumped out of the deposit to store off-peak energy and re-enters through turbines to recharge it (Kougias et al. 2019). Using a similar concept, underground siting in abandoned mines and caverns, could be developed reasonably quickly (Gül et al. 2020). Storage of energy as gravitational potential can also be implemented using materials other than water, such as rocks and sand. Pumped technology is a mature technology (Barbour et al. 2016; Rehman et al. 2015) and an important contributor of electricity storage, but with limited potential relative to the potential storage needs in future low-carbon electricity grids.

Batteries. There are many types of batteries, all having unique features and suitability (Table 6.5), but their key feature is their rapid response times. A rechargeable battery cell is charged by using electricity to drive ions from one electrode to another, with the reverse occurring on discharge, producing a usable electric current (Crabtree et al. 2015). While lead-acid batteries (LABs) have been widely used for automotive and grid applications for decades (May et al. 2018), lithium-ion batteries (LIBs) are increasingly being used in grid scale projects (Crabtree et al. 2015), displacing LABs. The rapid response times of batteries makes them suitable for enhanced frequency regulation and voltage support, enabling the integration of variable renewables into electricity grids (Strbac and Aunedi 2016). Batteries can provide almost all electricity services, with the exception of seasonal storage. LIBs, in particular, are able to store energy and power in small volumes and with low weight, making them the default choice for EVs (Placke et al. 2017).

Table 6.5 Technical characteristics of a selected range of battery chemistries, categorised as those which precede LIBs (white background), LIBs (yellow background) and post LIBs (blue background). With the exception of the All Solid-State batteries, all use liquid electrolytes. (1 =Mahmoudzadeh Andwari et al. 2017; 2 = (Manzetti and Mariasiu 2015; 3 =Placke et al. 2017.; 4 = Nykvist and Nilsson 2015; 5 =Cano et al. 2018; 6 = (Bloomberg Energy Finance 2019; 7 = You and Manthiram 2017; 8 = Fotouhi et al. 2017; 9 = IRENA 2017)

Battery Type	Technology Maturity	Life Span (Cycles)	Energy Density (Wh/L)	Specific Energy (Wh/kg)	Price (USD/kWh) in 2017
Lead Acid	High	300-800 [5]	102-106 [5]	38-60 [5]	70-160 [5]
Ni MH	High	600-1,200 [5]	220-250 [5]	42-110 [5]	210-365 [5]
Ni Cd	High	1,350 [2]	100 [2]	60 [2]	700
High temperature Na batteries	High	1,000 [5]	150-280 [8]	80-120 [1]	315-490 [8]
LIB State of art	High	1,000-6,000 [5]	200-680 [3]	110-250 [3]	176 [6]
LIB energy optimised	Under Development		600-850 [3]	300-440 [3]	
Classic Li Metal (CLIM)	Under Development		800-1050 [3]	420 – 530 [3]	
Metal Sulfur (Li S)	Near Commercialisation	100-500 [5]	350-680 [3, 8]	360-560 [3, 8]	36-130 [5]
Metal Sulfur (Na S)	Under Development	5000-10,000 [8]			
Metal Air (Li/air)	Under Development	20-100 [5]		470-900 [4]	70-200 [5]
Metal Air (Zn/air)	Under Development	150-450 [5]		200-410 [4]	70-160 [5]
Na ion	Under Development	500 [7]		600 [7]	
All Solid-State	Under Development			278-479 [3]	

EV batteries are expected to form a distributed storage resource as this market grows, both impacting and supporting the grid (Staffell, I. and Rustomji, M. et al. 2016). Drawbacks of batteries include relatively short lifespans and the use of hazardous or costly materials in some variants. While LIB costs are decreasing (Schmidt et al. 2017a; Vartiainen et al. 2020), the risk of thermal runaway, which could ignite a fire (Gur 2018; Wang et al. 2019a), and concerns about long-term resource availability (Sun et al. 2017; Olivetti et al. 2017), and global cradle-to-grave impacts (Peters et al. 2017; Kallitsis et al. 2020) need to be addressed.

The superior characteristics of LIBs will keep them as the dominant choice for EV and grid applications in the medium-term (*high confidence*). There are, however, several next-generation battery chemistries (Placke et al. 2017), which show promise (*high confidence*). Cost reductions through economies of scale are a key area for development. Extending the life of the battery can bring down overall costs and mitigate the environmental impacts (Peters et al. 2017). Understanding and controlling battery degradation is therefore important. The liquid, air-reactive electrolytes of conventional LIBs are the main source of their safety issues (Gur 2018; Janek and Zeier 2016), so All-Solid-State Batteries, in which the electrolyte is a solid, stable material, are being developed. They are expected to be safe, durable and to have higher energy densities (Janek and Zeier 2016). New chemistries and concepts are being explored, such as lithium sulphur batteries to achieve even higher energy densities (Van Noorden 2014; Blomgren 2017) and sodium chemistries, because sodium is more abundant than lithium (Hwang et al. 2017). Cost-effective recycling of batteries will address many of the sustainability issues and prevent hazardous and wasteful disposal of used batteries (Harper et al. 2019). Post-LIB chemistries include metal sulfur, metal-air, metal ion (besides Li) and All-Solid-State Batteries.

Compressed Air Energy Storage (CAES). Off-peak electricity is used to compress air in a reservoir – either in salt caverns for large scale, or in high pressure tanks for smaller scale installations. While conventional CAES has used natural gas to power compression, new low carbon CAES technologies, such as isothermal or adiabatic CAES, control thermal losses during compression and expansion (Wang et al. 2017c). Fast responses and higher efficiencies occur in small-scale CAES installations, scalable to suit the application and competitive with batteries as a distributed energy store, offering a flexible, low maintenance alternative (Luo et al. 2014; Venkataramani et al. 2016).

CAES is a mature technology in use since the 1970s. There have not been many installations to date (Wang et al. 2017b), however. While the prospects for CAES are good, with an excellent global geological storage potential of about 6.5 PW (Aghahosseini and Breyer 2018), a high initial investment is required. Higher efficiencies and energy densities can be achieved by exploiting the hydrostatic pressure of deep water to compress air within submersible reservoirs (Pimm et al. 2014). Similar to PSH, CAES is best suited to bulk diurnal electricity storage for buffering renewable sources and services which do not need a very rapid response, but has far more siting options than PSH and poses few environmental impacts.

Liquid Air Energy Storage (LAES). Liquid air energy storage uses electricity to liquefy air by cooling it to -196 °C and storing it in this condensed form (largely liquid nitrogen) in large, insulated tanks. To release electricity, the 'liquid air' is evaporated through heating, expanding to drive gas turbines. Low-grade waste heat can be utilised, providing opportunities for integrating with industrial processes to increase system efficiency. There are clear, exploitable synergies with the existing liquid gas infrastructure (Peters and Sievert 2016).

LAES provides bulk daily storage of electricity, with the additional advantage of being able to capture waste heat from industrial processes. This technology is in the early commercial stage (Regen 2017; Brandon et al. 2015). Advances in whole systems integration can be developed to integrate LAES with industrial processes, making use of their waste heat streams. LAES uniquely removes contaminants in the air and could potentially incorporate CO_2 capture (Taylor et al. 2012).

Thermal Energy Storage (TES). Thermal energy storage refers to a range of technologies exploiting the ability of materials to absorb and store heat or cold, either within the same phase (sensible TES), through phase changes (latent TES), or through reversible chemical reactions (thermochemical TES). Pumped Thermal Energy Storage (PTES), a hybrid form of TES, is an air-driven electricity storage technology storing both heat and cold in gravel beds, using a reversible heat-pump system to maintain the temperature difference between the two beds and gas compression to generate and transfer heat (Regen 2017). TES technologies can store both heat and cold energy for long periods, for example in underground water reservoirs for balancing between seasons (Tian et al. 2019; Dahash et al. 2019), storing heat and cold to balance daily and seasonal temperatures in buildings and reducing heat buildup in applications generating excessive waste heat, such as data centers and underground operations.

TES has the potential to be much cheaper than batteries and has the unique ability to capture and reuse waste heat and cold, enabling the efficiency of many industrial, buildings, and domestic processes to be greatly improved (*high confidence*). Integration of this capability into energy systems is particularly important, as the global demand for cooling is expected to grow (*high confidence*) (Peters and Sievert 2016; Elzinga et al. 2014). Sensible TES is well developed and widely used; latent TES is less developed with few applications. Thermochemical TES is the least developed, with no application as yet (Prieto et al. 2016; Clark et al. 2020). The potential for high density storage of industrial heat for long periods in thermochemical TES (Brandon et al. 2015) is high, with energy densities comparable to that of batteries (Taylor et al. 2012), but material costs are currently prohibitive, ranging from hundreds to thousands of dollars per tonne.

Flywheel Energy Storage (FES). Flywheels are charged by accelerating a rotor/flywheel. Energy is stored in the spinning rotor's inertia which is only decelerated by friction (minimised by magnetic bearings in vacuum), or by contact with a mechanical electric motor. They can reach full charge very rapidly, their state of charge can be easily determined (Amiryar and Pullen 2017) and they operate over a wide range of temperatures. While they are more expensive to install than batteries and supercapacitors, they last a long time and are best suited to stationary grid storage, providing high power for short periods (minutes). Flywheels can be used in vehicles, but not as the primary energy source.

Flywheels are a relatively mature storage technology, but not widely used, despite their many advantages over electrochemical storage (Dragoni 2017). Conventional flywheels require costly, high tensile strength materials, but high-energy flywheels, using lightweight rotor materials, are being developed (Amiryar and Pullen 2017; Hedlund et al. 2015).

Supercapacitors, aka Ultracapacitors or Double Layer Capacitors (Scap). Supercapacitors consist of a porous separator sandwiched between two electrodes, immersed in a liquid electrolyte (Gur 2018). When a voltage is applied across the electrodes, ions in the electrolyte form electric double layers at the electrode surfaces, held by electrostatic forces. This structure forms a capacitor, storing electrical charge (Lin et al. 2017; Brandon et al. 2015) and can operate from -40 to 65°C.

Supercapacitors can supply high peaks of power very rapidly for short periods (seconds up to minutes) and are able to fulfil the grid requirements for frequency regulation, but they would need to be hybridised with batteries for automotive applications. Their commercial status is limited by costly materials and additional power electronics required to stabilise their output (Brandon et al. 2015). Progress in this area includes the development of high energy supercapacitors, LIB-supercapacitor devices (Gonzalez et al. 2016) and cheaper materials (Wang et al. 2017a), all providing the potential to improve the economic case for supercapacitors, either by reducing manufacturing costs or extending their service portfolio.

Redox Flow Batteries (RFB). Redox flow batteries use two separate electrolyte solutions, usually liquids, but solid or gaseous forms may also be involved, stored in separate tanks and pumped over or through electrode stacks during charge and discharge, with an ion-conducting membrane separating the liquids. The larger the tank, the greater the energy storage capacity; whereas more and larger cells in the stack increase the power of the flow battery. This decoupling of energy from power enables RFB installations to be uniquely tailored to suit the requirements of any given application. There are two commercially available types today: vanadium and zinc bromide and both operate at near ambient temperatures, incurring minimal operational costs.

RFBs respond rapidly and can perform all the same services as LIBs, with the exception of onboard power for EVs. Lower cost chemistries are emerging, to enable cost-effective bulk energy storage (Brandon et al. 2015). A new membrane-free design eliminates the need for a separator and also halves the system requirements, as the chemical reactions can coexist in a single electrolyte solution (Navalpotro et al. 2017; Arenas et al. 2018).

Power to fuels (PtX). The process of using electricity to generate a gaseous fuel, such as hydrogen or ammonia, is termed power-to-gas (P2G), and limited quantities of these fuels can be injected into well-established gas networks (Gül et al. 2020), with the added benefit of decarbonising gas (Brandon et al. 2015), and combined cycle gas turbines can be converted to run on hydrogen. For greater compatibility with existing gas systems and appliances, the hydrogen can be methanated using captured carbon (Thema et al. 2019), however methane has high global warming potential and its supply chain emissions have been found to be significant (Balcombe et al. 2013).

PtX can provide all required grid services, depending on how it is integrated. While the roundtrip efficiency of converting electricity to fuel and back again can be low, there is still a need for distributable fuels (hydrogen, methane, ammonia, synthetic hydrocarbons), for example in energy systems lacking the potential for renewables and/or many applications requiring the high energy density of chemical storage, such as transport of heavy goods and heating/cooling of buildings (Gül et al. 2020). Research into more efficient and flexible electrolysers which last longer and cost less is needed (Brandon et al. 2015).

<u>Hydrogen and Reversible Hydrogen Fuel Cells (H/RHFC).</u> Hydrogen is a flexible fuel with diverse uses, capable of providing electricity, heat and long-term energy storage for grids, industry and transport and has been widely used industrially for decades (Section 6.4.5.1). Hydrogen can be stored in great quantities in geological formations at moderate pressures, often for long periods, providing seasonal storage (Gabrielli et al. 2020). A core and emerging implementation of PtX is hydrogen production through electrolysers. Hydrogen is a carbon-free fuel holding three times the amount of energy held by an equivalent mass of petrol, but occupying a larger volume. An electrolyser uses excess electricity to split water into hydrogen and oxygen through the process of electrolysis. A fuel cell performs the reverse process of recombining hydrogen and oxygen back into water, converting chemical energy into electricity (Elzinga et al. 2014). Reversible hydrogen fuel cells (RHFCs) can perform both functions in a single device, however they are still in the pre-commercial stage, due to prohibitive production costs.

Hydrogen can play an important role in the deep decarbonisation of a range of sectors globally and has been shown to be the most cost-effective option in some cases, as it builds on existing systems (Staffell et al. 2018). Fuel cell costs need to be reduced and the harmonies between hydrogen and complementary technologies, such as batteries, for specific applications, need to be explored further. Hydrogen provides resilience in future low carbon energy systems, covering windless gaps in renewable generation. Research in this technology is focused on improving roundtrip efficiencies, which can be as high as 80% with recycled waste heat and in high-pressure electrolysers, incorporating more efficient compression (Matos et al. 2019). Photo-electrolysis uses solar energy to directly generate hydrogen from water (Amirante et al. 2017).

6.4.4.2 Societal Dimensions of Energy Storage

Public awareness knowledge about electricity storage technologies, their current state, and potential role in future energy systems is limited. For instance, people do not perceive energy system flexibility and storage as a significant issue or assume storage is already taking place. Public perceptions differ across storage technologies. Hydrogen is considered a modern and clean technology, but people also have safety concerns. Moreover, the public is uncertain about hydrogen storage size and the possibility of storing hydrogen in or near residential areas. Battery storage both on household and community level was perceived as slightly positive in one study However, financial costs are seen a main barrier. The potential of electric vehicle batteries to function as flexible storage is limited by the current numbers of EV owners and concerns that one's car battery might not be fully loaded when needed.

6.4.5 Energy Transport and Transmission

The linkage between energy supply and transformation, on the one hand, and energy use on the other is facilitated by various mechanisms for transporting and transmitting energy. As the energy system evolves, the way that energy is transmitted and transported will also evolve.

6.4.5.1 Hydrogen: Low-Carbon Energy Fuel

Hydrogen (H2) is considered to be one of the key low-carbon energy fuels (Nozari and Karabeyoğlu 2015). Hydrogen at could offer a versatile, clean, and flexible fuel for a decarbonised future (Fuel Cells and Hydrogen Joint Undertaking 2019). Hydrogen is carbon-free and has a high conversion efficiency (do Sacramento et al. 2013) to electricity. Hydrogen can be utilised for provision of electricity, heat, industry, transport energy storage. Currently, hydrogen has limited applications. For example, nearly all of the hydrogen consumed in the U.S. is currently used by industry (e.g., refining petroleum). Furthermore, there are currently about 80 fuel cell power plants operating in the U.S. with a total of about 190 MW of electric generation capacity (EIA 2020). The Japanese government has invested in development of hydrogen fuel infrastructure, as a part of hydrogen economy (Meti 2017), aimed at facilitating deployment of hydrogen-based fuel cell vehicles. Hydrogen fuel-cell based technology could support heavy-duty vehicles and potentially lighter vehicles for longer-range journeys (Kendall and Pollet 2012; European Policy Solutions 2018; Office for Low Emission Vehicles 2018; (Department for Transport 2017). Hydrogen could provide low-carbon heat to buildings (replacing natural gas in boilers) and industrial processes (e.g., as feedstock for the chemical industry or direct reduction of iron ore (Vogl et al. 2018). Hydrogen could replace natural gas-based electricity generation, particularly to balance variable renewable generation and demand. Hydrogen could also provide long-term storage in order to deal with extreme events, such as low output of renewable generation for long durations or a significant increase in demand driven by extreme weather conditions.

Hydrogen can be produced from fossil fuels, biological material, and water (Dodds et al. 2015). Low-carbon can be produced from: (a) steam methane reforming (SMR) with carbon capture and storage (CCS) (Sanusi and Mokheimer 2019), (b) autothermal reforming (ATR) with CCS (Zhou et al. 2020), (c) coal/biomass gasification with CCS (Hu et al. 2020), and (d) from low/zero carbon energy sources such as renewables and nuclear (e.g., High Temperature Reactors (HTR) (Jaszczur et al. 2016) in an electrolysis process (Schmidt et al. 2017a). Hydrogen production costs vary regionally and are highly dependent on resource availability (i.e., fossil fuel resources for producing 'blue' hydrogen and renewable resources for 'green' hydrogen). In Table 6.6, the characteristics of different hydrogen production processes and estimated costs via fossil fuels are presented (Committee on Climate Change 2018). For natural gas reforming, the CCS will add on average 50% on the capital expenditure (CAPEX) and 10% for fuel as well as 100% of operation expenditure (OPEX), while for coal gasification, the CAPEX and fuel cost is expected to increase (compared to without CCS) 5% and OPEX by 130% (IEA 2019; Staffell et al. 2018) Three main electrolysis technologies are: alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis cells (SOECs), where the estimated CAPEX and efficiencies are provided in Table 6.7 (IEA 2019; Fasihi and Breyer 2020).

Table 6.6 Key performance and cost characteristics of different hydrogen production technologies

Technology	Efficiency (%)		Carbon Intensity (kg_{CO2}/kg_{H2})	Cost Estimates* (USD/kg_{H2})	
	Current	Future		2025	Long term
SMR with CCS	65	74	1.4-3.9	1.36-2.13	1.45-2.43
Advanced gas reforming with CCS	-	81	0.9-3.2	1.19-1.92	1.15-1.96
Coal gasification with CCS	58	58	3.7-6.1	2.90	2.26-3.07
Biomass gasification with CCS	44-48	46-60	Potential to achieve negative emissions	4.52	2.73-5.42

***USD/GBP exchange rate is assumed to be 0.78 (Average rate in 2019).**

Table 6.7 Efficiency and cost characteristics of different hydrogen production through electrolysis technologies

Technology	Efficiency (%)			CAPEX (USD/kW$_e$)		
	Current	2030	Long term	Current	2030	Long term
Alkaline Electrolysers	63-70	65-71	70-82	500-1400	400-850	200-700
PEM Electrolysers	56-60	63-68	67-74	1100-1800	650-1500	200-900
SOEC Electrolysers	74-81	77-84	77-92	2800-5600	800-2800	500-1000

One advantage of SMR/ATR based processes is that they can use existing gas infrastructure for transport of natural gas. SMR/ATR processes can therefore be performed close to hydrogen demand centers, bypassing transportation challenges. Residual carbon emissions present an important challenge, however. The largest reduction in GHG emissions could be achieved by coupling highly-concentrated CO_2 sources from CO_2-emitting sectors with carbon-free hydrogen or electrons from renewable power in so called "Power-to-fuel" (or Power-to-X) pathways (Artz et al. 2018). This includes the increase in efficiency and reduction in cost of the gas-conversion technologies (e.g., SMR, ATR) (Committee on Climate Change 2018) as well as development of advanced hydrogen production technologies (e.g., mainly electrolysers; SOEC) (Schmidt et al. 2017a).

Utilising remote renewable energy resources to produce hydrogen and then transport these fuels over long distances could facilitate cost-effective global energy system decarbonisation (high confidence) (See also Box6.7 and Box 6.8). For example, electricity generated from renewables (e.g., wind in north of Europe and solar in Africa) can be used to produce hydrogen that is then transported for use elsewhere (Ameli et al. 2020). Hydrogen in remote areas, however, would require hydrogen transportation over long distances, including local distribution and intermediate storage capabilities needed to deliver hydrogen to the demand centers (e.g., refueling station or power plants) (Office of energy efficiency et al. 2018).

Based on the amount of the produced hydrogen as well as the distance to the demand, hydrogen delivery infrastructure, including pipelines, trucks, storage facilities, compressors, and dispensers, would be required (Office of energy efficiency et al. 2018; Hydrogen Europe 2018). For large-scale transportation, hydrogen must be pressurised to be delivered in a form of compressed gas or liquid and the national transmission system should be used. Due to the lower energy density of hydrogen compared to natural gas, about three times more hydrogen by volume is required to supply the same energy. Therefore, maintaining the security of supply is more challenging in hydrogen networks, and hence linepack (Ameli et al. 2017; Ameli et al. 2019) will play a critical role (Linepack is the volume of hydrogen stored in the pipelines and can be used to meet abrupt diurnal changes in hydrogen demand.). In the UK, in the Iron Mains Replacement Programme (Committee on Climate Change 2018), the existing low pressure gas distribution pipes are being converted from iron to plastic for health, safety, and environmental reasons. This new distribution gas infrastructure will be able to transport hydrogen within districts. Gasunie in Netherlands has used an existing 12km natural gas pipeline for transporting hydrogen(Gasunie 2019). Yet, new pipelines for hydrogen transmission at national level are likely to be required, which imposes investment issues. In order to transport hydrogen in medium and high-pressure networks, reinforcements in compressor stations as well as pipeline construction routes are required (Gasunie 2019).

Hydrogen is not currently cost effective, but it could have a significant role in future energy systems (*high confidence*). Key challenges for hydrogen are: (a) cost-effective low/zero carbon production, (b) delivery infrastructure cost, (c) linepack management, (d) maintaining hydrogen purity, (e) minimising hydrogen leakage (Office of energy efficiency and renewable energy 2018), and (f) adapting end-use appliances (e.g., replacing the boilers). Hence, a global hydrogen-based economy is not considered to be fully cost effective at present (Eberle et al. 2009) unless an appropriate storage medium, which can provide short term to long term capabilities, could be established. For direct large-scale hydrogen storage, mediums such as salt caverns (Andersson and Grönkvist 2019; Caglayan et al. 2020) and hydrides (Schlapbach and Züttel 2001) has been investigated, however there are still many challenges from techno-economic perspective, due to large size and minimum pressure requirements of the sites (IEA 2019). This makes them not suitable for small scale and short term storage purposes. Consequently, alternative carbon-free fuels such as ammonia (NH3), which stores hydrogen (comprises 17.8% of hydrogen by mass without involving the carbon molecule) may become more attractive (Kobayashi et al. 2019; Lan et al. 2012).

Ammonia; Promising Hydrogen Energy Carrier. Hydrogen could be used with captured CO_2 to produce synthetic fuels (Power-to-X) such as ammonia, methanol, synthetic methane, and synthetic oil products (IRENA 2019d). Such alternative fuels are drop-in solutions to move away from fossil fuel as: (a) they can be used in existing infrastructure in the intensive industries and in the transport sector (Gumber and Gurumoorthy 2018; Schemme et al. 2017; Transport and Environment 2018; DENA 2017), (b) they can benefit from the liquefied natural gas (LNG) industry, and (c) it is easier to store than hydrogen (IRENA 2019b). In the transport sector, synthetic methane might not be the best solution as leaks are likely, but methanol could be used efficiently with the existing infrastructures, especially for aviation and shipping (Schemme et al. 2017). In the short-term, the role of hydrogen could first be to form methanol or other CO_2 based fuels (Gumber and Gurumoorthy 2018). Even if CO_2 is captured from fossil fuel combustion process, CO_2 emissions will remain. Hence, to reduce emissions to zero, CO_2 should be captured from biomass or from direct air capture (DAC) technologies (IRENA 2019b). CO_2 emissions can be reduced by 74% to 93% for methanol and 54% to 87% for e-methane as compared to conventional production routes (IEA 2019a). As demonstrated in (IRENA 2019b; Creutzig et al. 2019a) The royal society 2019; IEA 2019), ammonia is the most cost-effective synthetic fuel.

Storing ammonia and transporting ammonia is more cost effective than hydrogen, however direct use of ammonia for electricity generation produces substantial NO_x emissions, which have high toxicity (*high confidence*). Liquid ammonia has recently been considered as a highly capable hydrogen carrier (Zamfirescu and Dincer 2008; Nam et al. 2018; Soloveichik 2016; due to its high gravimetric and volumetric hydrogen storage (Zamfirescu and Dincer 2008). The energy density of ammonia is 38% higher than liquid hydrogen (Osman and Sgouridis 2018). Moreover, ammonia is readily condensable (liquefied at 0.8 MPa, 20°C), which provides economically viable hydrogen storage and supply systems. At present, major ammonia production is used in fertilisers (approximately 80%), followed by many industrial processes such as refrigeration, petrochemicals, and food (Jiao and Xu 2018). Ammonia production and transport are established industrial processes (~180 million tonnes/year (Valera-Medina et al. 2017), and hence ammonia is considered to be a scalable and cost-effective fuel source.

Current hydrogen and ammonia production processes are mainly reliant on fossil fuels (Goldmann and Dinkelacker 2018) (Figure 6.18). As presented, ammonia can be produced from low/zero carbon generation technologies such as RES (Kraemer 2018) and nuclear (Jaszczur et al. 2016).

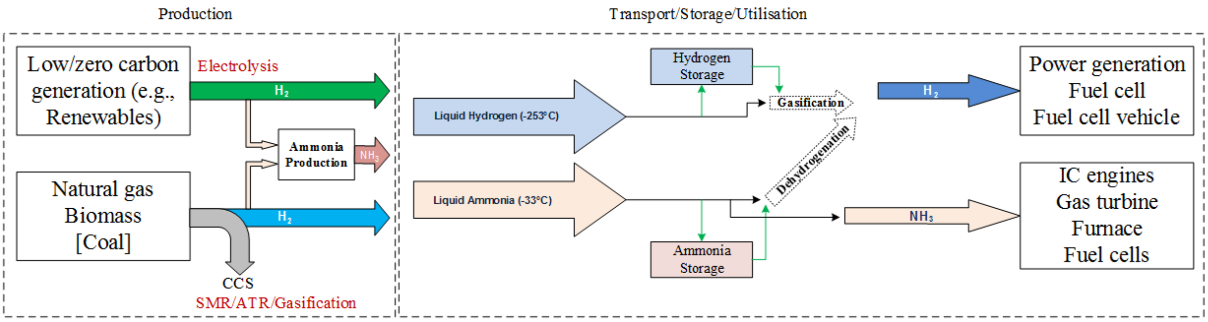


Figure 6.18 Ammonia and hydrogen production, transport and utilisation

Hydrogen, can be liquefied in order to be transported at volume via sea and without pressurisation, while liquefying hydrogen (LH$_2$) requires temperature of –253ºC and is therefore energy-intensive, and hence increasing the cost of transport (Office of energy efficiency et al. 2018; Hydrogen Europe 2018). Additionally, once the gas reaches its destination it needs to be re-gasified before being used, adding further cost. A demonstration project is under development in Australia, exploring the alternative options of exporting liquefied hydrogen to Japan (Yamashita et al. 2019).

Ammonia is produced from synthesising hydrogen with nitrogen, and then shipped via sea in liquid form. Ammonia is a liquid fuel at temperatures of below -33ºC and is therefore more straightforward and less costly to transport than LNG or LH$_2$ (Singh et al. 2018). There is currently energy loss of about 15-25% when cracking ammonia back into hydrogen (Bell and Torrente-Murciano 2016; Hansgen et al. 2010; Montoya et al. 2015), which could favor the use of ammonia, rather than hydrogen in certain sectors. A project where ammonia could be exported from Saudi Arabia to Japan is under consideration (Nagashima 2018).

Liquid organic hydrogen carriers (LOHCs) could be an alternative option for transporting hydrogen at ambient temperature and pressure, which considered to be more novel process than liquefied hydrogen or ammonia (Suh et al. 2012; Züttel et al. 2003). The main advantage of LOHCs is the similarity to oil products properties, and hence they can be transported by oil tankers and stored in oil tanks, so the oil infrastructure can be re-used. A project is under development in Brunei to export hydrogen to Japan using LOHCs (Kurosaki 2018). One of the potential LOHCs is methylcyclohexane (MCH), with toluene as the carrier molecule. However, toluene is toxic, and an alternative LOHC is dibenzyltoluene, which is much more expensive than toluene currently (IEA 2019).

Challenges around hydrogen energy fuels including safety, storage, and consumption, requires new devices and techniques to facilitate large-scale use of hydrogen/ammonia (*high confidence*). Hydrogen should be gasified to be used or injected into the pipelines, while ammonia can be used directly as a fuel without any phase change for internal combustion (IC) engines, gas turbines, and furnaces. Ammonia can be used also in low and high temperature fuel cells (Lan and Tao 2014), whereby both electricity and hydrogen can be produced without any NO$_x$ emissions. Furthermore, ammonia provides the flexibility to be dehydrogenated for hydrogen-use purposes. Ammonia is considered a carbon-free sustainable fuel for power generation, since in a complete combustion, only water and nitrogen are produced (Valera-Medina et al. 2017). Ammonia could facilitate management of variable RES, due to its cost-effective grid-scale energy storage capabilities (storing ammonia is more cost effective than storing hydrogen). In this regard, production of ammonia from low/zero carbon generation technologies along with ammonia energy recovery technologies could play a major role in forming an ammonia economy to support decarbonisation (Afif et al. 2016). The combustion process of ammonia is very similar to natural gas in gas turbines. However, due to low flammability of ammonia (Li et al. 2018), there are difficulties in the ignition as well as burning velocity compared to other fuels. Many studies

(Iki et al. 2015; Valera-Medina et al. 2017; Nozari and Karabeyoğlu 2015) investigated the role of the ignition mechanism control, and it is shown that through the existing technologies, emission will be produced (Nozari and Karabeyoğlu 2015; Ryu et al. 2014). The Life Cycle Assessment (LCA) for ammonia (produced by renewables) for power generation indicates lower emissions (0.08 Kg CO_2 eq./MJ) compared to natural gas (0.13 Kg CO_2 eq./MJ) (Bicer and Dincer 2017). It is demonstrated that by taking into account the life cycle (e.g., wind turbine manufacturing and power plants), there are still GHG emissions. Therefore, for carbon-free large-scale power generation, new devices and techniques should be developed.

All hydrogen energy carriers face safety issues around flammability, toxicity and safe storage of medium in order to be viable options for transporting, storing hydrogen at scale (Eberle et al. 2009) . Particularly, beside the GHG emissions in the LCA of hydrogen energy carriers, a key challenge in use of ammonia is NOx emissions (released from nitrogen and oxygen combustion) and unburned ammonia, which are a substantial air pollution risk, not only from a health perspective (toxicity) but also from visibility perspective, EPA 2001).To deal with NO_x emissions, a special catalyst would be adapted to combine ammonia with nitrogen to decrease the nitrogen oxides production (Bicer and Dincer 2017). Due to low flammability of hydrogen (Nilsson et al. 2016) and ammonia (Li et al. 2018), a stable combustion in the existing gas turbines is not feasible. In this regard, recent developments have demonstrated that the percentage of hydrogen that can be used in gas turbines was successfully increased, and further development of gas turbines would enable operation of 100% hydrogen by 2030 (Simens 2019).

6.4.5.2 Electricity Transmission

Given the significant geographical variations in the efficiency of renewable resources across different regions and continents, high capacity and long length electricity transmission infrastructure could facilitate cost effective deployment of renewable generation (*high confidence*). In general, the case for increased electricity interconnection across different countries and regions rests on three core benefits: (i) enhanced security of supply (ii) enhanced operation efficiency (e.g. regional load-generation levelling) and (iii) more cost-effective deployment of renewables due to the fact that the efficiency of renewable resources significantly vary across different regions and continents, as does the scale of transmission network available to harness these resources (Arderne et al. 2020) and mitigate regional variations in renewable energy output over diurnal, seasonal, and inter-annual cycles. Hence, the diurnal and seasonal characteristics of different renewable energy source such as wind, PV would need to be considered in optimising the generation and network design and therefore maximising the asset utilisation to support the integration of renewable technologies. During winter, i.e. high wind output and low PV output, the grid can facilitate the North to South flows while during summer, the flows reverse- though there may be significant variation over diurnal cycles or associated with continental weather patterns. Therefore, a regional (global) approach to deploying renewables at the most resourceful locations could facilitate a more cost-effective energy system decarbonisation compared to a local approach, while enhancing operational efficiency and reducing the need for investment in peaking plant needed to meet security of supply requirements. Fully coordinated deployment of renewable sources in Europe by 2030 would save 150 GW of renewable energy source capacity being built while producing the same amount of renewable energy by, for example, harnessing of the climatic dipole between southern and northern Europe with more efficient location of renewable energy sources and maximising use of high-productivity regions (Newbery et al. 2013). That is, put simply, building more wind in areas with high wind potential and more solar in areas with better solar connectivity and increasing transport between regions to allow effective sharing of resources. This could save more than USD180bn of capital expenditure by 2030 (ibid).

Although the cost of renewables continues to decrease, it would still be important to find the balance between the cost-benefits of local against regional deployment strategies that need to be supported by sufficient transmission. In this context, there is growing interest in interconnection in the European power system in order to reduce congestion constraints driven by growth in renewable generation and support electricity trading across the EU. Transmission infrastructure is not the only solution for enhancing renewables uptake. For example, in the USA further investment in e.g. localised storage may be preferable to larger-scale transmission investments (Lovins 2017) and (Jayadev et al. 2020). In general, interconnection is more cost-optimal for countries that are geographically relatively close to each other, and can benefit from the diversity of their energy mixes and usage (Schlachtberger et al. 2017). Under strong sector coupling, the benefit of transmission expansion may decrease but does not disappear (Brown et al. 2018). Global co-operation in improving reliability of electricity systems and ability to mitigate the consequences of global warming will require a globally interconnected system that would improve both economic performance and reliability (Breyer et al. 2019; Bogdanov et al. 2016). Such developments are not without price, however, and, amongst other concerns, raise issues surrounding land use and resource acquisition for materials necessary for renewables developments. Such issues are discussed in (Vakulchuk et al. 2020) and (Capellán-Pérez et al. 2017).

There were also potential benefits of wider integration between different regions, e.g. MENA (Middle East & North Africa) and Europe for renewable energy resource sharing, for example in (Schaber et al. 2012; Rodríguez et al. 2014; Haller et al. 2012). There are clearly benefits to utilising continental climatic variation to share renewable energy resources (Kaspar et al. 2019) and could also help support economic development in MENA regions, as well as temporal differences allowing countries to share the burden of meeting peak demand across wider geographic ranges. As scenario analysis demonstrated in (Bloom et al. 2020), the benefit-to-cost ratio for western-eastern interconnection in the USA is 2.9. Beyond Europe, intercontinental interconnectors, e.g. East-West (Middle East/Asia – Europe) have also been considered to enable utilisation of geographically spread renewables across the globe. Increased interconnectivity of large-scale grids also allows the aggregation of "smart grid" solutions such as flexible demand from wet devices (Labeeuw et al. 2015) or use of electric vehicles (EVs) as demand response (Rassaei et al. 2015) to support regional system performance. Larger scale integration of systems can facilitate resource sharing of such assets over wide geographic ranges.

The State Grid Corporation of China is building a 1.1 million Volt transmission line (12 GW voltage source converter transmission technologies: the right fit for the application capacity) that will be able to transport electricity over 2,000 miles (Fairley 2016). This project is the first of its kind in the world, and a major step towards the development of international and intercontinental mega-grids. High voltage Alternative Current (HVAC) and High voltage Direct Current (HVDC) technologies are well-established and widely used for bulk power transmission. HVDC is used with underground cables or long-distance overhead lines where HVAC is infeasible or not economic. HVDC or UHVAC have been developed to provide very long distance transport (over 2,500 km) and very high amounts of power (over 7 GW), but there has been strong interest in developing new technologies that might expand the size of transmission corridors and/or improve the operational characteristics. Potential new technologies include low-frequency AC (LFAC) (J et al. 2016; Fischer et al. 2012; Ngo et al. 2016) and half-wave AC (HWACT) transmission (Nicola et al. 2014). LFAC is technically feasible, but the circumstances in which it is the best economic choice (compared to HVDC or HVAC) still needs to be established (Xiang et al. 2016). HWACT is restricted to very long distances, however, there has not yet been demonstration of HWACT, so its practical technical feasibility is not yet fully proven. There are still a number of technological challenges which require novel solutions to be developed in the near future. These include the higher capacity of (ultra) HVDC (Hammons and Lescale 2012), protection systems for DC or hybrid AC-DC networks (Franck et al. 2017; Chaffey 2016), improvement in cabling technology, including the use of superconductors and nanocomposites (Ballarino et al. 2016).

Market design, regulation and policy framework related to the development of regional interconnections should be aligned with the decarbonisation agenda in order to support cost effective deployment of renewable generation (*high confidence*). In addition, there are commercial barriers for further enhancement of cross-border transmission. This includes integration of the cross-border trading into the electricity market (Newbery and Strbac 2011) that would address the asymmetrical impacts and provide appropriate market signal that can incentivise such development in an economically efficient manner (Pudjianto et al. 2016). The asymmetric impact on the welfare of stakeholders causes arbitrage trades shifting away from the market equilibriums, which may further cause potential delay in the development of cross-border interconnector (as it is not yet clear how the investment cost of interconnection should be allocated / recovered, although there is growing support to the concept that would allocate the cost in accordance with the benefits delivered to market participant). Development of cross-border interconnection may also require a new business model which provides incentives for investment and efficient operation, manages risks and uncertainties and facilitates coordinated planning and governance (Poudineh and Rubino 2017).

Optimising the design and operation of the interconnected transmission system, both onshore and offshore grids, also require more integrated economic and reliability approach (Moreno et al. 2012; ENTSO-E 2020) to ensure the optimal balance between the economics and the provision of system security while maximising the benefits of smart network technologies. In this regard, as an example, studies such as (Konstantelos et al. 2017; Koivisto et al. 2019; Energinet 2020) investigate the potential benefits of offshore grid including wind farms and interconnectors in the North Sea.

Network load characteristics driven by the profiles of generation and demand, circuit losses, reliability characteristics (risk factors) and the need for maintenance will also play a crucial role in determining the optimal system design, particularly for the offshore system (Djapic et al. 2008). All of these factors including the risk associated with future uncertainty should be considered in designing and operating offshore network or long-transmission system in order to derive strategic decisions to maximise the long-term benefits and utilisation of the network investment (De Sa and Al Zubaidy 2011; De Sa and Al Zubaidy 2011; Du 2009; Strbac et al. 2014). Moreover, public support for extending transmission systems may be low (Perlaviciute et al. 2018; Vince 2010).

In this context, market design, infrastructure regulation and policy framework related to the development of regional interconnections should be aligned with decarbonisation agenda, which remains one of the main drivers of power system reform and redesign in Europe (Newbery et al. 2013; ENTSO-E 2020b).

6.4.6 Demand Side Mitigation Options from an Energy Systems Perspective

End users and demand-side measures are fundamental to an integrated approach to low carbon energy systems The implementation of mitigation options, such as wind parks, CCS, and nuclear power plants, may be inhibited when these options are not acceptable to actors Moreover, end users, including consumers, governments, businesses and industry, would need to adopt the relevant energy supply options, and then use these in the intended way user adoption can be a key driver to scale up markets for low carbon technologies This section discusses which factors shape the likelihood that different mitigation options are adopted and used by end users, focusing on consumers; Section 6.7.6.1 discusses the effects of policies to promote mitigation actions.

End users can engage in a wide range of actions that would reduce carbon emissions, including:

- use of energy sources and carriers with low carbon emissions. They can produce and use their own renewable energy (e.g., install solar PV, solar water heaters, heat pumps), buy shares in a renewable energy project (e.g., wind shares), or select a renewable energy provider.
- adoption of technologies that support flexibility in energy use and sector coupling, facilitating balancing demand and renewable energy supply. This would reduce the need to use fossil fuels to meet energy demand when renewable energy production is low, and put less pressure on deployment of low-emission energy supply systems. Examples are technologies to store energy

(e.g., batteries and electric vehicles) or that automatically shift on or off appliances (e.g., fridges, washing machines), depending on the availability of renewable energy.

- adoption of energy-efficient appliances and systems, and increase of resource efficiency of end uses so that less energy is required to provide the same service. Examples are insulating buildings, and passive or energy positive buildings.
- change behavior to reduce overall energy demand or to match energy demand to available energy supplies. Examples include adjusting indoor temperature settings, reducing showering time, reducing car use or flying, or operating appliances when renewable energy production is high.
- purchase and use products and services that are associated with low GHG emissions during their production (e.g., reduce dairy and meat consumption) or for transporting products (e.g., local products). Also, end users can engage in behavior supporting a circular economy, by reducing waste (e.g., of food), sharing products (e.g., cars, equipment), and refurbishing products (e.g. repair rather than buying new products) so that less products are produced.

Various factors shape whether mitigation options are feasible and considered by end users, including contextual factors, individual abilities, and different types of motivation. Mitigation actions can be facilitated and encouraged by targeting these barriers and enablers (see 6.7.6.2).

Contextual factors, such as physical and climate conditions, infrastructure, available products and technology, regulations, institutions, culture, and financial conditions define the costs and benefits of mitigation options that enable or inhibit their adoption. Geographic location and climate factors may make some technologies, such as solar PV or solar water heaters, impractical (Chang et al. 2009). Culture can inhibit efficient use of home heating or PV (Sovacool and Griffiths 2020), low carbon diets (Dubois et al. 2019), and advanced fuel choices (Van Der Kroon et al. 2013). Also, favorable financial conditions promote the uptake of PV (Wolske and Stern 2018), good facilities increase recycling (Geiger et al. 2019), and vegetarian meal sales increase when more vegetarian options are offered.

Mitigation actions are more likely when individuals feel capable to adopt them (Pisano and Lubell 2017; Geiger et al. 2019), which may depend on income and knowledge. Low-income groups may lack resources to invest in refurbishments and energy-efficient technology with high upfront costs (Andrews-Speed and Ma 2016; Chang et al. 2009; Wolske and Stern 2018). Yet, higher income groups can afford more carbon-intensive lifestyles (Golley and Meng 2012; Namazkhan et al. 2019; Frederiks et al. 2015; Santillán Vera and de la Vega Navarro 2019; Mi et al. 2020; Wiedenhofer et al. 2017).). Knowledge of the causes and consequences of climate change and of ways to reduce GHG emissions is not always accurate, but lack of knowledge is not a main barrier of mitigation actions (Boudet 2019).

Motivation to engage in mitigation action, reflecting individuals' reasons for actions, depends on general goals that people strive for in their life (i.e., values) that affect which types of costs and benefits of actions people consider and prioritise when making choices. People who strongly value protecting the environment and other people are more likely to consider climate impacts and to engage in a wide range of mitigation actions than those who strongly value individual consequences of actions, such as pleasure and money (Taylor et al. 2014; Steg 2016). People endorse different values, and not only have the goal to maximise self-interest. This implies that they consider different types of costs and benefits when making choices (Gowdy 2008; Steg 2016). Specifically, they not only consider individual, but also affective, social, and environmental costs and benefits.

First, people are more likely to engage in mitigation behavior (i.e., energy savings, energy efficiency, resource efficiency in buildings, renewable energy generation) when they believe such behavior has more individual benefits than costs (Harland et al. 1999; Steg and Vlek 2009; Kastner and Matthies 2016; Kastner and Stern 2015; Kardooni et al. 2016; Wolske et al. 2017; Korcaj et al. 2015), including financial benefits, convenience, comfort, autonomy, and independence in energy supply (Wolske and

Stern 2018). Yet, financial consequences seem less important for decisions to invest in energy-efficiency and renewable energy production than people indicate (Zhao et al. 2012).

Second, people are less likely to engage in mitigation behaviors that are unpleasurable or inconvenient (Steg 2016), and more likely to do so when they expect to derive positive feelings from such actions (Pelletier et al. 1998; Steg 2005; Carrus et al. 2008; Brosch et al. 2014; Taufik et al. 2016). Positive feelings may be elicited when behavior is pleasurable, but also when it is perceived as meaningful (Bolderdijk et al. 2013b; Taufik et al. 2015).

Third, social costs and benefits can affect climate action (Farrow et al. 2017), although people do not always recognise this (Nolan et al. 2008; Noppers et al. 2014). People engage more in mitigation actions when they think others expect them to do so and when others act as well (Rai et al. 2016; Harland et al. 1999; Nolan et al. 2008). Being part of a group that advocates mitigation actions encourages such actions (Biddau et al. 2016; Fielding and Hornsey 2016; Jans et al. 2018). Talking with peers can reduce uncertainties and confirm benefits about adoption of renewable energy technology (Palm 2017), and peers can provide social support (Wolske et al. 2017). People may engage in mitigation actions when they think this would signal something positive about them (Griskevicius et al. 2010; Milinski et al. 2006; Kastner and Stern 2015; Noppers et al. 2014). Social influence can also originate from political and business leaders (Bouman and Steg 2019). For example, GHG emissions are lower when legislators have strong environmental records (Jensen and Spoon 2011; Dietz et al. 2015).

Fourth, mitigation actions, including saving energy and hot water, limited meat consumption, and investments in energy efficiency, resource efficiency in buildings, and renewable energy generation are more likely when people more strongly care about others and the environment (Balcombe et al. 2013; Wolske et al. 2017; Steg et al. 2015; Van Der Werff and Steg 2015; Kastner and Matthies 2016; Kastner and Stern 2015; Zhang et al. 2013). People across the world generally strongly value the environment (Steg 2016; Bouman and Steg 2019), suggesting that they are motivated to mitigate climate change. The more individuals are aware of the environmental impact of their behavior, the more they think their actions can help reduce such impacts, which strengthens their moral norms to act accordingly (Steg and de Groot 2010; Jakovcevic and Steg 2013; Chen 2015; Wolske et al. 2017).

Initial mitigation actions can encourage engagement in other mitigation actions when people experience that such actions are easy and effective (Lauren et al. 2016), and when initial actions make them realise they are a pro-environmental person, motivating them to engage in more mitigation actions so as to be consistent (van der Werff et al. 2014; Lacasse 2015, 2016; Peters et al. 2018). This implies it would be important to create conditions that make it likely that initial mitigation actions motivate further actions.

6.4.7 Summary of Mitigation Options

Table 6.8 summarises the costs of electricity generation from different sources. Table 6.9 summarises the barriers and enablers for implementing different mitigation options in energy systems. The feasibility of different options can be enhanced by removing barriers and/or strengthening enablers of the implementation of the options. The Table also indicates whether the feasibility of options may differ across context (e.g., region), time (e.g., 2030 versus 2050), scale (e.g., small versus large) and temperature goal (e.g., 1.5°C versus 2°C).

Table 6.8 Summary of cost and performance characteristics of key energy technologies. *[Figure is under development. What is shown is a sample of some of the levelised cost information gathered to date.]*

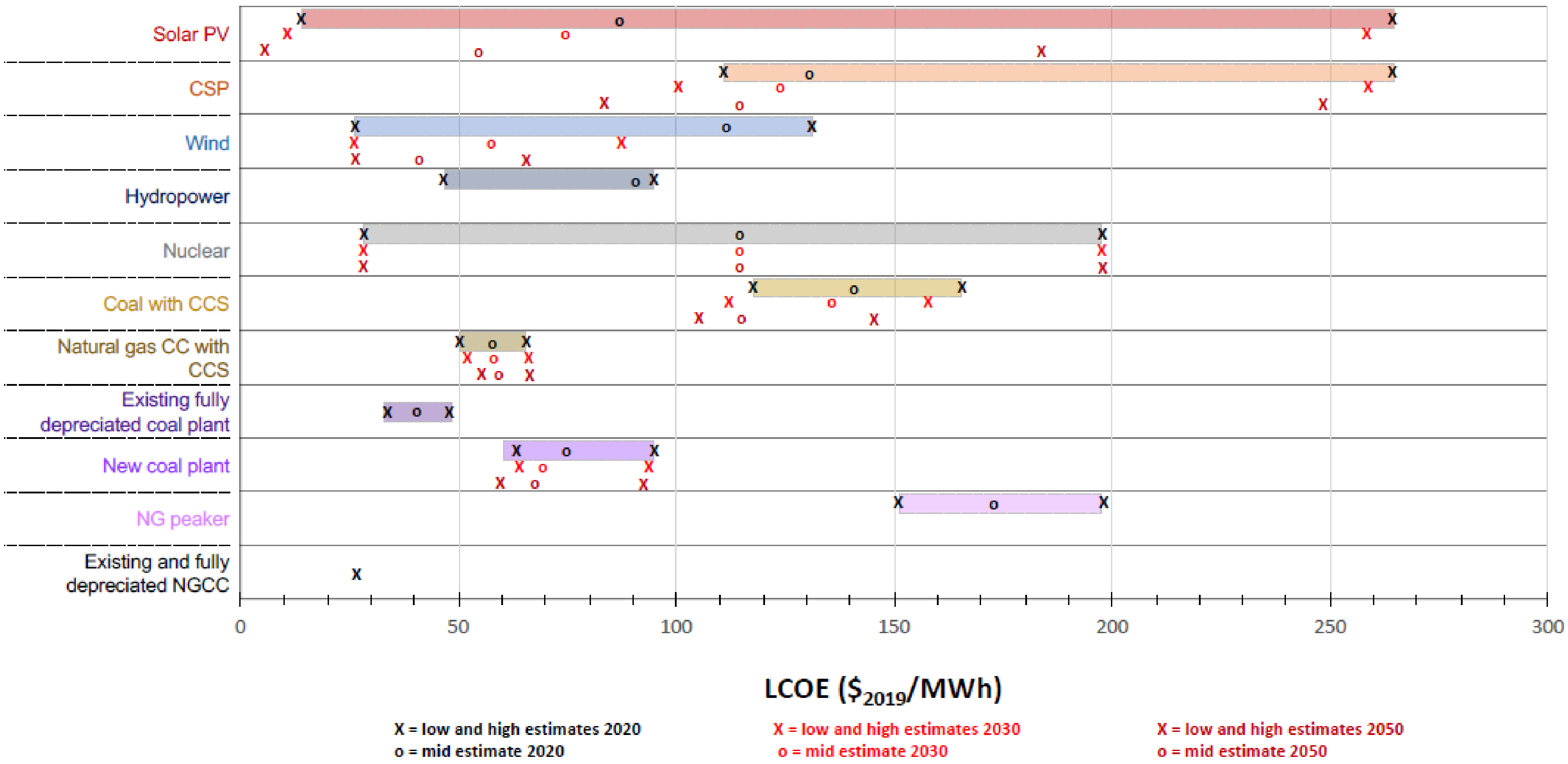


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Table 6.9 Summary of the barriers and enablers influencing the feasibility of different mitigation options.
Yellow shading signifies the indicator has a positive impact on the feasibility of the option. Light brown shading signifies the indicator has mixed positive and negative effect on the feasibility of the option. Dark brown shading indicates the indicator has a negative impact on the feasibility of the option. A 0 signifies the indicator does not affect the feasibility of the option, NA that the indicator is not applicable for the option, NE indicates no evidence, and LE means limited evidence whether the indicator affects the feasibility of the option. LoA = level of agreement; LoC = Level of evidence

Mitigation Options	Solar Energy		Wind energy		Hydroelectric power		Nuclear		Carbon Dioxide Capture, Utilization, and Storage		Bioenergy		Fossil fuel phaseout		Geothermal		Energy storage for low-carbon grids -		Demand side mitigation		System integration	
	variable definition	**scenarios mean and inter-quartile range**	**variable definition**	**scenarios mean and inter-quartile range**	**variable definition**	**scenarios mean and inter-quartile range**	**variable definition**	**scenarios mean and inter-quartile range**	**variable definition**	**scenarios mean and inter-quartile range**	**variable definition**	**scenarios mean and inter-quartile range**	**variable definition**	**scenarios mean and inter-quartile range**	**variable definition**	**scenarios mean and inter-quartile range**	**variable definition**	**scenarios mean and inter-quartile range**	**variable definition**	**scenarios mean and inter-quartile range**	**variable definition**	**scenarios mean and inter-quartile range**
Scenario Results from AR6 database for Paris consistent policies (1.5 and 2°C): full scenario ensamble if not otherwise specified. Scenario number changes by reporting variable	Solar electricity: 2020 and 2050 (EJ)	3->64 [27-102]	Wind electricity: 2020 and 2050 (EJ)	6->63 [40-81]	Hydro electricity: 2020 and 2050 (EJ)	16->26 [21-30]	Nuclear electricity: 2020 and 2050 (EJ)	10->23 [14-27]	CCS in 2050 (GtCO2)	8 [7-28]	Primary energy biomass: 2020 and 2050 (EJ)	58 -> 126 [97-146]	Primary energy fossil: 2020 and 2050 (EJ)	479 -> 267 [193-344]	Primary energy geotherma: 2020 and 2050 (EJ)	1 -> 5 [1-9]	Capacity Electricity Storage in 2050 (GW)	4500 [3038-5600]	CO2 emissions from demand: 2020 and 2050 (GtCO2)	19 -> 10 [6.4-12.4]	Share of wind&solar in electricity: 2020 and 2050 (%)	9 -> 54 [41-72]
Indicators	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**	**Feasibility barriers or enablers**	**Role of context, scale, time, temperature goal**
Geophysical																						
Physical potential	LoA=5|LoC=5	Limited in higher latitudes	LoA=5|LoC=5	unevenly distributed over the globe and the time of the year	LoA=4|LoC=4	Limited in water scarce regions and where good suitable locations are taken, also could be impacted by climate change	LoA=3|LoC=3	In case of expansion of nuclear (doubling or tripling of current capacity levels), some countries could face limits in finding new sites for construction.	LoA=4|LoC=5	Limited in some sectors - including CO2 utilization, bioenergy with CCS etc	LoA=4|LoC=5	Sufficiently high waste biomass resources at several locations	LoA=5|LoC=5	Large physical resource to remain unutilized	LoA=4|LoC=4	Large potential but very site specific. Up-front cost particularly high and associated with uncertainities for drilling	LoA=5|LoC=5	The size of grid networks, customer demands, storing capacity and location of devices, their advantages and limitations, cost, lifetime, and impacts on the environment must be considered during selection decision. The sources of power production; renewable or fossil fuels, must also be accounted, as well as the integration with incumbent systems.	NA		LoA=4|LoC=4	This requires tapping newly developed integration facilities, such as facilities that combine hardware testing at proper scale with simulation. Monitoring is also challenging due to big data.
Geophysical resources (incl geologica storage capacity)	LoA=4|LoC=5	Not limited by materials	LoA=4|LoC=5	Not limited by materials	LoA=4|LoC=4	Not limited by materials to build dams	LoA=5|LoC=5		LoA=5|LoC=5	Large overall geologic storage potential. But limited in some crucial regions	LoA=5|LoC=5	Bioenergy crop potential is hindered by several factors but is high in some regions	LoA=5|LoC=5	Mining and depletion of non-renewable resources would reduce	LoA=3|LoC=3	For direct thermal uses, the technical potential is estimated at 10 to 312 EJ/yr (IPCC 2011). For electricity generation, technical potential estimated be between 118 EJ/yr (to 3 km depth) and 1,109 EJ/yr (to 10 km depth).	LoA=5|LoC=4	Due to a wide range of technologies, it is available.	NA		0	
Land use	LoA=4|LoC=5	Limeted in urban areas	LoA=3|LoC=5	limited in some areas (e.g. Europe), but extremely large regional variations	LoA=4|LoC=4	covering large land areas with water	LoA=4|LoC=4	Normally, it's a low footprint for land. Some nevertheless point out to the longevity of permanent storage for radioactive waste, low in land use footprint, but long span in utilisation	LoA=4|LoC=5	Less than several other mitigation options (not considering bioenergy)	LoA=5|LoC=5	Very large land use implications	LoA=3|LoC=4	Uncertain but could be positive if it reduces the need for CDR	0		LoA=5|LoC=3	While some type of storage require no specific characteristic (e.g. salt caverns), some others need suitable lands and areas, or special safety considerations.	NA		0	
Environmental-ecological																						
Air pollution	LoA=4|LoC=4	minimal effects in manufactruing	LoA=4|LoC=4	minimal effects in manufactruing	LoA=4|LoC=4	a clean energy option, but some emission from concrete to construct dams, and emissions from the water buddies	LoA=4|LoC=5		LoA=5|LoC=5	Reduces air pollution from fossil sector as an indirect advantage based on technological specifications	LoA=3|LoC=4	Inefficient domestic biomass has negative air pollution effects but well-coordinated deployment does not have such a high impact	LoA=5|LoC=5	Large air pollution benefits especially of coal phaseout	LoA=|LoC=	geothermal power plants reject a lot more heat than other type plants per unit of electricity generated	LoA=5|LoC=5	The storing techniques and devices can also affect the environment positively. The positive impacts may be the decreased impact on global warming and a lesser effect emerging from the use of fossil fuels. Some materials and manufacturing processes do emit GHGs, either directly, or due tot he source of the power they use.	LoA=|LoC=		LoA=5|LoC=4	Energy System Integrated (ESI) takes a holistic view of the electricity, gas, and heat sectors to deliver a clean, reliable, and affordable energy system. By using the synergies within and between sectors, ESI aims to increase flexibility in the energy system, maximise the integration of renewable energy and distributed generation, and reduce environmental impact.
Toxic waste, ecotoxicity and eutrophication	LoA=4|LoC=4	Reclycing rates crucial	LoA=|LoC=	Issues related to recycling of wind turbines	LoA=5|LoC=5		LoA=3|LoC=3	Issue of radioactive waste, long term solutions are needed. Limited impacts to ecosystems	0		LoA=4|LoC=4	Can use waste as a fuel resource	LoA=4|LoC=4	Considerable benefits but replacements could increase other waste	LoA=|LoC=		LoA=4|LoC=3	Disposal of devices material may also emerge as a constraint to the environment if not deployed and managed appropriately. Some devices use critical resources and materials which are eco-toxic or polluting, particularly during extraction and manufacturing.	LoA=|LoC=		LoA=3|LoC=3	Potential of reducing NOx by optimal use of ammonia
Water quantity and quality	LoA=5|LoC=5		LoA=|LoC=		LoA=5|LoC=5	affect hydrologic flows, water temperature in streams, and downstream habitat	LoA=3|LoC=4	Needs substantive amount of water for cooling purposes	LoA=5|LoC=5	Water use increases and could lead to plant retirements in several water stressed regions	LoA=4|LoC=4	Can use waste as a fuel resource	LoA=4|LoC=5	Uncertain but could be positive if it reduces the need for CDR. Other positive impacts due to reduced needs for fracturing	LoA=|LoC=	Impact on ground water depletion and contamination, living organisms, seismcity	LoA=4|LoC=4	The extraction of materials and maunfacturing processes for some devices use a considerable amount of fresh water. The wastewater generated during different processes (e.g., manufacturing, treatment, recycling) can be dangerous. If wastewater penetrates into the ground and flows into surface waters, it can create many problems for human health, so capture and treatment of contaminated wastewater is very important and vital.	LoA=|LoC=		LoA=3|LoC=3	ESI aims to increase flexibility in the energy system such as the link between electricity-water nexus, which can optimse the quantity of water
Biodiversity	LoA=3|LoC=3	Concerns in protected areas	LoA=3|LoC=3	can be mimimized by careful site selection of wind power facilities	LoA=5|LoC=5	damages habitat, thermal pollution, hypoxia, fish migration, increased water consumption/evaporation	LoA=4|LoC=4		0		LoA=5|LoC=5	Very large water use	LoA=5|LoC=5	Improved biodiversity outlook	LoA=|LoC=	Impact on living organisms	LoA=4|LoC=4	Direct impacts on ecosystems largely come from material extraction; some devices require more impactful materials than others. Some technologies would directly encroach on ecosystems due to their land use.	LoA=|LoC=		NE	
Technological																						
Simplicity	LoA=5|LoC=5	Globally simple	LoA=5|LoC=5		LoA=5|LoC=5		LoA=4|LoC=4		LoA=5|LoC=5	Logistically challenging requiring widespread infrastructural coordination	LoA=4|LoC=5	Either negative or positive depending on whether measures such as biochar utilization are implemented	LoA=4|LoC=4	Uncertain. Depends on replacement technologies	LoA=|LoC=	Globally simple	LoA=3|LoC=3	Compared to capacity expansion, it is simpler. However, some technologies are still in early stage of development and need further development in order to be widely employed.	LoA=|LoC=		LoA=4|LoC=3	Appart from meters, hardwars, and simulation platforms, different incentives, decision-making processes, and access to capital due to location or scale need to result in very different energy systems and approaches to energy system integration
Technology scalability	LoA=5|LoC=5	Globally scalable	LoA=3|LoC=5	technology is ready, but not all supply chain	LoA=5|LoC=5	Globally scalable	LoA=4|LoC=4	Qualified and skilled labor force could be an issue in case of expansion in nuclear new builds	LoA=4|LoC=5	Technology development occuring but at slow rate	LoA=5|LoC=5	Logistically complex especially with BECCS	LoA=4|LoC=4	Uncertain. Depends on replacement technologies	LoA=|LoC=	Globally scalable but need to look beyond electrical use only and support end-use sectors such as heating in industry, agriculture, buildings	LoA=3|LoC=3	Different technologies in different sizes are available. Most ES technologies have large- and small-scale options; some are specifically modular, or have built-in flexibility of scale.	LoA=|LoC=		LoA=4|LoC=3	From distribution level to transmisssion level is scalable
Maturity and technology readiness	LoA=5|LoC=5	Globally mature	LoA=5|LoC=5	globally mature	LoA=|LoC=	very matured	LoA=3|LoC=3	GenIII/IIII+ reactors need to be scaled up more to improve their technology readiness	LoA=4|LoC=4	Low readiness in several supply chain components	LoA=5|LoC=4	Several technological avenues present but requires upgradation in other areas	LoA=4|LoC=5	Several regions have already demonstrated coal phaseout already	LoA=|LoC=	Mature but potential for improvement particularly for high depth potential	LoA=3|LoC=3	Some technologies are still in early stage of development and need further attention to be widely deployed. Some are very mature.	LoA=|LoC=		LoA=4|LoC=4	Currently developments in renewable energy, energy storage, and power electronic technologies have been experienced. However, also gaps have been identified: improving decision support tools and their data requirements; definition of key performance indicators; smart strategies for resource on demand implementation including energy storage; real time knowledge of parameters; common data repositories; optimization and control structures to integrate energy systems; improved design, installation and control.
Economic																						
Costs in 2030 and long term	LoA=4|LoC=4	Low and declining	LoA=4|LoC=4	declining	LoA=|LoC=		LoA=3|LoC=3	Costs for new builds are country/region specific. Life time extensions are cheaper than new builds.	LoA=4|LoC=5	Costs are uncertain though decline is projected with learning	LoA=4|LoC=4	Waste biomass utilization has led to some readiness	LoA=4|LoC=5	Overall impacts are positive when environmental externalities are considered. However, there could be large stranded assets	LoA=2|LoC=2	Potential for reduction for high depth potential thanks to technolgy progress in drilling. Typical costs for geothermal power plants USD 1 870 to USD 5 050/ kW depending on size and technology. Potential for LOCE reduction in the long-term. USD 0.04-0.14 to 0.037 to 0.11 by 2050	LoA=3|LoC=3	Various energy storage technologies also differ in their cost (capital, running and maintenance, labor, and replacement after some intervals). Although there is some prediction in the literature, however there is uncertainty and perfect insight is not possible.	LoA=|LoC=	Some low demand options have high upfront costs	LoA=5|LoC=5	The amount of cost reduction has been reported in the reference.
Employment effects and economic growth	LoA=4|LoC=4	Globally beneficial	LoA=4|LoC=4	globally beneficial	LoA=3|LoC=3	Beneficial	LoA=3|LoC=3	Depends on size of countries: smaller countries benefit less, big countries benefit more. Also depends on the number of units to be constructed: first two units have minimal effect.	LoA=3|LoC=4	Potential increase in employment in several allied sectors	LoA=4|LoC=5	Technology costs are anticipated to reduce but fuel costs may rise leading to uncertain cost outlook	LoA=5|LoC=5	Low-carbon sources demonstrate good employment avenues. However, regional inequity may be present causing unemployment of fossil fuel sector workers	LoA=|LoC=	Little impact on employment and economic growth. High capital cost per unit	LoA=5|LoC=4	Skilled employment in manufacturing, maintenance and installation companies.	LoA=|LoC=		LoA=3|LoC=3	The cost reduction leads to economic growth through providing opportunity to invest in other fields. Furthermore, developing renewable energies can increase employment rate.
Socio-cultural																						
Public acceptance	LoA=4|LoC=4	high upfront costs and long payback periods may be barriers for adoption; not feasible for all households (e.g., apartments, rental houses)	LoA=4|LoC=4	Higher support for offshore; local wind projects might evoke resistance	LoA=3|LoC=3	New large hydropower is controversial in some areas if local residents and ecosystems are endangered and trust in government or companies is low	LoA=4|LoC=4	Acceptance is higher among those who percieve benefist for economy, climate change mitigation and energy security	LoA=4|LoC=2	Many people are unfamiliar with CCS, so have not formed fim opinions. Some firmly reject CCS, some are concerned that CCS may avoid that GHG emission reductions take place	LoA=3|LoC=3	biomass from waste products (e.g. food waste) more acceptable than grown-for-purpose energy crops	LoA=4|LoC=3	Coals and oil evaluated negatively, natural gas evaluated the least negative. Acceptability of fossil energy higher in countries that strongly rely on them	LoA=3|LoC=2	Perceived as relatively environmentally-friendly, but concerns about water scarcity, noise, smell, seismic risks of drilling, and landscape damage.	LoA=3|LoC=2	Awareness of storage technologies is low, and limited evidence varies across technologies; hydrogen is perceived to have advantages (clean, offers energy storage) and disadvantages (saftey concerns). Batteries are evaluated slightly positively, but are believed to be expensive, somewhat unsafe, and people are concerned about recycling options; for EV batteries, people are concerned about cars not being fully	LoA=4|LoC=3	Feasibilit if higher for options that do not require significant changes in lifestyles; feasibility will be higher when financial, legal and infrastructural barriers for demand side mitgation are removed. Not clear whether reported intentions will be translated into behaviour	LoA=3|LoC=2	Most evidence on different aspects of system integration, not system as a whole. Feasibility will be higher when invedtment costs are removed and privacy issues are addressed. Extending transmission lines is generally evaluated negatively. Energy indepence and being self sufficient positively evaluated
Effects on health and wellbeing	LoA=5|LoC=5	Globally beneficial	LoA=3|LoC=3	Effects on wellbeing via aesthetic issues and noise disturbances	0		LoA=|LoC=		0		0		0		LoA=|LoC=	Water quality in the area may be affected. Noise pollution	LoA=5|LoC=5	In addition to emission reductions, energy storage is also vital for essential service providers like healthcare sector which rely mainly upon energy storage. Safety issues for workers in material extraction, processing and component manufacture for some technologies.No issues at point of use, under normal operation, as long as hydrogen and battery safety is controlled.	0		LoA=4|LoC=3	Reducing air pollution prevents some diseass
Distributional effects	LoA=3|LoC=4	High upfront costs deter adoption in developing countries, despite low costs.Distribution of costs and benefits change as a funtion of design choices.	LoA=3|LoC=3	Some debate around the environmental justice of large wind farms because of land pressures and uneven development. This could be a barrier if it is not taken into account	LoA=3|LoC=3	Large hydropower could have negative impacts on livelihoods, so affecting distributional and equity aspects	LoA=|LoC=		NE		LoA=|LoC=	Labor conditions could determine impacts on poverty and equity. Regarding energy crops, there are concerns about land access and food security. Costs and benefits of energy crops could be unevenly distributed	0		LoA=|LoC=	The impacts on income poverty and inequality may be dependent of resource lifespan. Improving standards of living, energy access and water access	0		LoA=2|LoC=2	Low costs of energy that improves equity and reduce poverty, but high costs of modern equipment as a barrier could even stress inequality	0	
Institutional																						
Political acceptance	LoA=3|LoC=4	Opposed by fossil interests	LoA=3|LoC=4	Opposed by fossil interests	LoA=4|LoC=4	large reservoirs are becoming less socially accepted especially in developed nations due to environmental issues,	LoA=4|LoC=4	Lack of political acceptance	LoA=4|LoC=4	Very dependent on country	LoA=4|LoC=4	Usually positive	LoA=4|LoC=4	Several governments are indicating support for coal phaseout such as PPCA	LoA=|LoC=	Rather positive by and large.	LoA=5|LoC=5	General political acceptance and active promotion in the US, UK and Europe.	LoA=|LoC=		LoA=4|LoC=4	Government should provide incentives(e.g., a government can invest in high-voltage transmission, while individuals will not). It is needed to align the market design with low carbon agenda. System integration can provide evidence in this regard.
Institutional capacity and governance, cross-sectoral coordination	LoA=4|LoC=4	Need support for rapid scale up in developing countires	LoA=3|LoC=4	Need support for rapid scale up of electricity transmission	LoA=4|LoC=4	challenges could arise due to competition in water use (managing multipurpose reservoirs)	LoA=4|LoC=3	Lenghty licence process, not enough institutions and what they have created is not a sustainable process since everything is falling behind the schedule	LoA=5|LoC=5	Several new schemes globally incentivize CCUS sufficiently	LoA=4|LoC=5	Land-based mitigation need to be brought under market mechanisms swiftly	LoA=4|LoC=5	It would require change in fossil fuel subsidy mechanisms	LoA=|LoC=	Some countries are providing policy support in the form risk guarantees, investment grant to mitigate uncertain drilling operation outcomes and high up-front costs	LoA=4|LoC=3	Given concerns expressed about the competency of some communities and local authorities, there may well be a space for community, local government and private sector organisations to develop partnerships to deliver energy services in new, more flexible ways. It is not clear how such hybrid relationships may coevolve with storage and other	LoA=|LoC=	Voluntarily change	LoA=4|LoC=4	Government should provide incentives(e.g., a government can invest in high-voltage transmission, while individuals will not). It is needed to align the market design with low carbon agenda. System integration can provide evidence in this regard.
Legal and administrative feasibility	LoA=3|LoC=4	Electricity market reforms required	LoA=3|LoC=4	Electricity market reforms required	LoA=4|LoC=4	water rights, water markets in some regions	LoA=3|LoC=3		LoA=4|LoC=5	Need for robust monitoring and verification	LoA=4|LoC=5	Gauging actual carbon removal is difficult	LoA=5|LoC=4	Susceptible to leakage and other effects	0		LoA=4|LoC=3	The UK and Europe are exploring how to overcome these barriers and have been largely successful.	LoA=|LoC=	Voluntarily change does need legal and administrative support	LoA=4|LoC=4	Government should provide incentives(e.g., a government can invest in high-voltage transmission, while individuals will not). It is needed to align the market design with low carbon agenda. System integration can provide evidence in this regard.

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6.5 Climate Change Impacts on the Energy System

Various components of the current and future energy system, which are the basis for climate change mitigation, are also affected by a changing climate. These effects are not limited to the supply of renewable energy, which are often weather dependent, and can impact, both in a positive and negative manner, various aspects of the energy system. The impacts of climate change can be divided in three general areas: impacts on the energy supply, impacts on energy consumption and impacts on the vulnerability of electric power systems. Climate change influences the processes in the climate system in many interconnected time scales and thus also the energy system. For example, faults in electricity transmission due to wildfires (short time scale) can occur in the context of extreme heat waves (weekly time scale), which occur within the slow and steady warming of the climate system (long-term changes). The focus of this section is not on how climate affects the energy system, but on how the changes in climate impact drivers (e.g., increase temperature or drought) affect the ability of the energy system transformation to mitigate climate change (Figure 6.19).

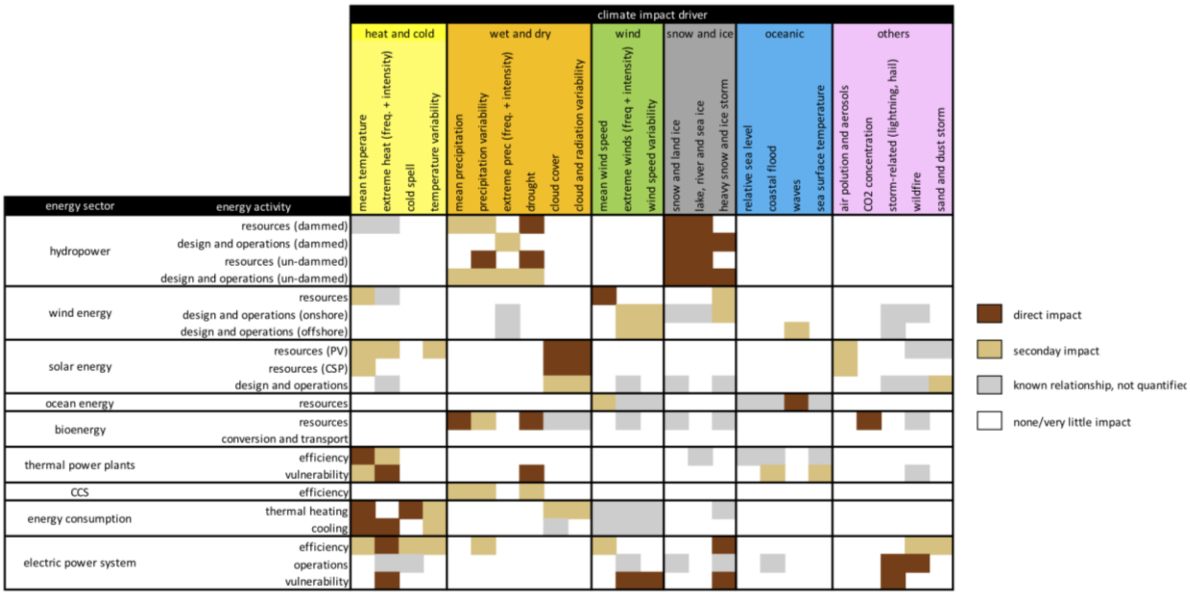


Figure 6.19 Relevance of key climatic impact drivers for major categories of the energy system. Direct impact indicates climatic impact drivers that directly affect the energy sector activity; secondary impact indicates impacts that indirectly affect the energy system activity. Non-quantified represents impacts mentioned in the literature but whose effect is unquantified.

6.5.1 Impacts on Energy Supply

The increased weather-dependency of future low-carbon power systems amplifies the possible impacts of climate change. However, there is high agreement and robust evidence that *globally* climate change impacts on hydro, wind and solar power potentials are small and should not compromise climate mitigation strategies. At the regional and local level, however, climate change effects on RE potentials can be significant. Climate change impacts on bioenergy potentials are complex and more uncertain because of uncertainties associated with the crop response to climate change, and future land and water availability. Climate change is expected to reduce efficiency of thermal generation and increase the risk of power plant shutdowns during droughts. Additional cooling water needs of carbon capture and storage (CCS) can increase these risks.

6.5.1.1 Hydropower

Impacts of climate change on hydropower is highly regional and may be positive or negative. High latitudes in the northern hemisphere are estimate to experience increased runoff and hydropower potential. Regions where a decreased runoff is expected may have reduced hydropower production as well as increase water conflict among different economic activities. (*high confidence*)

The production of hydropower is directly related to the availability of water. Changes in runoff and seasonality, as well as changes in temperature and precipitation intensity, may influence hydro electricity production by impacting from the technical elements of the power plants to the structure of the dam (IHA 2019). Increased precipitation intensity may affect hydropower production by increasing trash, vegetation and silting of reservoirs or increasing the amount of water spilled resulting in erosion at the toe of the dam and may require security upgrades. Extreme weather jeopardises structure security that needs to be taken into account on the production (Schaeffer et al. 2012; IHA 2019). At the same time, the increased precipitation increases water availability promoting hydropower production. Climate change can also lead to higher air temperature leading to surface evaporation and reduction of water storage, and to loss of equipment efficiency (Ebinger and Vergara 2011; Fluixá-Sanmartín et al. 2018; Hock et al. 2019; Mukheibir 2013). Climate change can alter the demands for water use by other sectors that often rely on stored water in multi-purpose reservoirs. Typically the increased need of water for irrigation or industry can affect the availability of water for hydropower generation (Solaun and Cerdá 2017; Spalding-Fecher et al. 2016). At the same time, higher temperature increase glacier melting, increasing water availability for hydropower, as well as changes the timing of snow and ice melt that may require upgrading in storage capacity and adaptation of the hydropower plant management for fulling exploiting the increase in water availability.

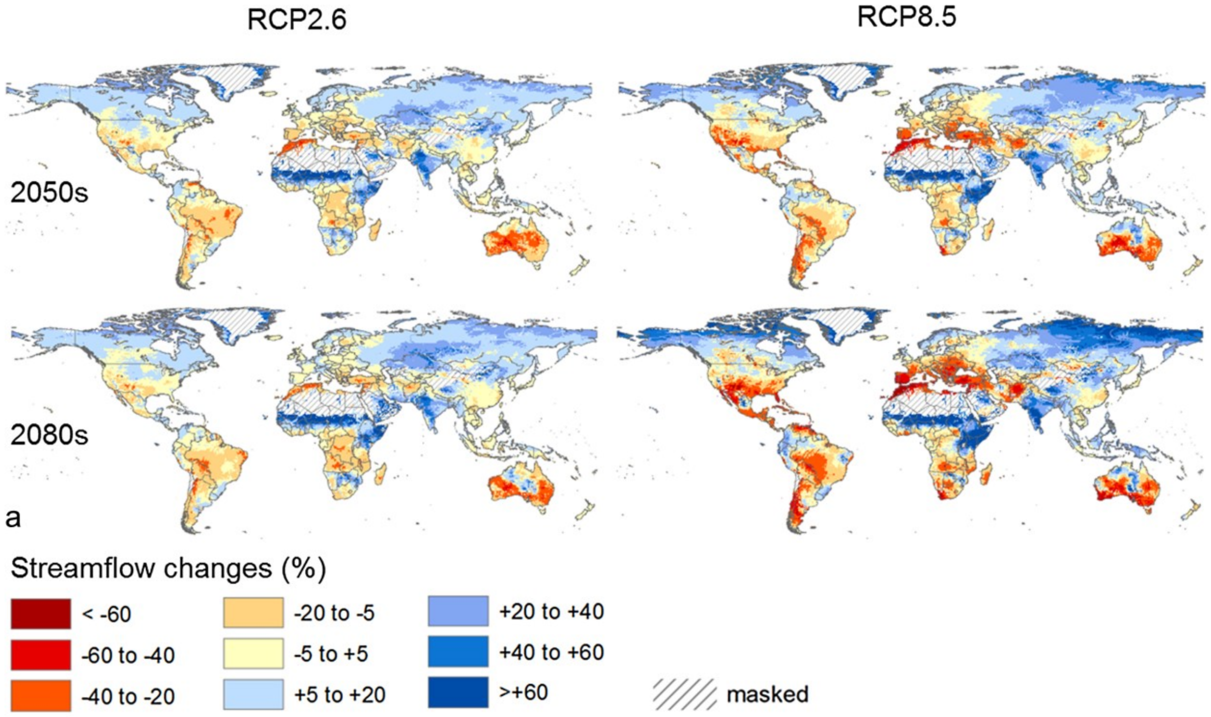


Figure 6.20 Global spatial patterns of changes in gross hydropower potential based on climate forcing from five climate models. Changes are shown for the 2050s (upper) and the 2080s (lower) for the low emission scenario (RCP2.6; left) and highest emission scenario (RCP8.5; right) scenarios relative to the control period (1971–2000).

[Source: (van Vliet et al. 2016c), Figure 5].

Although climate change may affect hydropower production in a number of ways, most studies have focused on how changes in river flow would affect hydropower potential (Cronin et al. 2018a; Solaun and Cerdá 2019; Schaeffer et al. 2012). The conclusions regarding climate change impacts on hydropower vary due to differences in modelling assumptions and methodology, such as choice of the GCMs and hydrological model, choice of metrics (e.g., projected production vs. hydropower potential), level of modelling details between local and global studies, reservoir operation assumptions and how they compete with other reservoir purposes, accounting for other competing water and energy users and how they are impacted by climate change (Turner et al. 2017; van Vliet et al. 2016c). Nonetheless, the analyses are consistent in demonstrating that globally, the impact of climate change on hydropower is small; however regionally they are variable both positively and negatively (*high confidence*). Decreases in gross global hydropower potential are estimated from a very slight increase around 2050 (Hamududu and Killingtveit 2012) to between –0.4% (GCM-GHM ensemble mean for the low emission scenario) and –6.1% (for the highest emission scenario) for the 2080s compared to 1971–2000 (Figure 6.20) (van Vliet et al. 2016a).

Regional changes in hydropower production are estimated from 5–20% increases for most areas in high latitudes due to increase of water availability due to increased precipitation and glacier melting (van Vliet et al. 2016c; Turner et al. 2017) to decreases by 5–20% in areas with increased drought conditions (Cronin et al. 2018a). Streamflow has been consistently shown to increase by 2080 in high latitudes of the northern hemisphere, and parts of the tropics such as central Africa and Southern Asia while decreasing in the USA, southern and central Europe, Southeast Asia and southern South America, Africa and Australia (van Vliet et al. 2016b,c). Studies are consistent in indicating an increase in hydropower production in the high latitudes of the northern hemisphere including Canada, Nordic European Countries and Russia, as well as, north-west South America, Southern Asia, equatorial Africa and developing Pacific. Decrease in streamflow and hydropower production are indicated for the USA, central and southern Europe, Middle East, central Asia and Southern South America. A disagreement among studies is found regarding hydropower production in China, central South America, and partially in Southern Africa.

6.5.1.2 Wind Energy

Climate change is not expected to substantially impact future wind resources that could compromise the ability of wind energy to mitigate climate change. Changing wind variability may have small to modest impact on increased backup energy and storage needs; however, studies focus mostly on Europe. (*high confidence*)

Long-term global wind energy resources are not expected to substantially change in future climate scenarios (Karnauskas et al. 2018; Yalew et al. 2020a; Pryor et al. 2020). However, recent research has indicated consistent shifts in the geographic position of atmospheric jets under the high emission scenarios (Harvey et al. 2014), which would decrease wind power potentials across the Northern Hemisphere mid-latitudes and increase across the tropics and Southern Hemisphere. However, the various climate models used for investigating future wind resources differ in the degree of which they can reproduce the current wind resources and wind extremes, thus questioning how robust their prediction of future wind resources are (Pryor et al. 2020).

At the regional scale, there are many studies on regional future wind resources. For Europe, there is medium evidence and moderate agreement wind resources will increase in N. Europe and decrease in S. Europe (Moemken et al. 2018; Carvalho et al. 2017; Devis et al. 2018). For North America, there is low agreement in future changes and in most studies is lower than year-to-year variations (Johnson and Erhardt 2016; Wang et al. 2020b; Costoya et al. 2020; Chen 2020). For Brazil, studies show increases in resource-rich areas (Ruffato-Ferreira et al. 2017; de Jong et al. 2019), and for China no robust changes are identified (Xiong et al. 2019). None of the cited studies takes into account the fine-scale dependence of wind power on the topography and wind direction (Sanz Rodrigo et al. 2016), or on the effect of expanding wind energy extraction on local and regional climate (Lundquist et al. 2019). Increasing extreme wind speeds due to climate change, which can damage wind turbines, have been identified for some regions (Pryor and Barthelmie 2013; Pes et al. 2017). However, projected changes over Europe and the contiguous USA are expected to be within the estimates embedded in the design standards of wind turbines (Pryor and Barthelmie 2013).

Temporal changes in wind power generation can be affected by climate change. Wind generation in Europe is projected to decrease mainly in summer and autumn, with increases in winter in northern-central Europe but decreases in the southernmost Europe (Carvalho et al. 2017). Towards 2100, intra-annual variations are expected to increase in most of Europe, except the Mediterranean area, especially for the second half of the 21st century (Reyers et al. 2016). However, the changes in seasonality attributed to climate change may reflect natural multidecadal variability, which indicates that there is still significant uncertainty in assessing climate change impacts on temporal variability of wind generation (Wohland et al. 2019b). Wind speeds may get more homogeneous over large geographical regions in Europe due to climate change, which means that likelihood of large areas experiencing high or low wind speed simultaneously may increase (Schlott et al. 2018). This indicates less benefits in transmission of wind generation between countries and can lead to increased system integration costs. Under the high emission scenarios in Europe, a modest increase (up to 7 %) of backup energy towards the end of the 21st century is reported (Wohland et al. 2017), as countries are more likely to experience generation shortfall simultaneously. Both increased likelihood for long periods of low wind generation and increase in seasonal wind variability are reported to cause increase of backup energy and storage needs in most of Central, Northern and North-Western Europe (Weber et al. 2018). However, (Van Der Wiel et al. 2019) reports that impact of climate change is substantially smaller than interannual variability, and no significant impact of climate change on the occurrence of extreme low renewable energy production events in Europe is observed. Other studies suggest that if European power systems can take into account weather variability in wind power, it can also cope with climate change impacts (Ravestein et al. 2018). Changes in wind generation variability caused by climate change are reported also for the USA (Haupt et al. 2016; Losada Carreño et al. 2018), with modest impacts on power system operation (Craig et al. 2019).

6.5.1.3 Solar Energy

As with wind power, climate change is not expected to substantially impact solar radiation at the surface and compromise the ability of solar energy to mitigate climate change. Increases in downward solar radiation in some models and scenarios are often counterbalanced by decreasing efficiency due to rising surface air temperatures, which show significant increases in all models and scenarios. (*high confidence*)

For solar PV, increases in downward solar radiation will often be counterbalanced by decreasing efficiency due to rising surface air temperatures, which show significant increases in all models and scenarios (Jerez et al. 2015; Bartók et al. 2017). Yet the effect of efficiency loss is smaller than what can be expected from changes in solar radiation and clouds in most regions, and it is possible that future PV technologies will have improved performance characteristics with respect to their irradiance or temperature response (Müller et al. 2019). Climate change projections show decreases in cloud cover in the subtropics (around –0.05%/year) including SE N. America, wide parts of Europe and China, N. S. America, South Africa and Australia (medium agreement, medium evidence). Some of these trends reflect changes in pollution levels in e.g. India in the emission scenarios (Ruosteenoja et al. 2019).

In terms of solar radiation for CSP, there are potential for future increases in production in many parts of the globe, with few exceptions such as the North of India (Wild et al. 2017). In contrast to PV, CSP output increases with increasing temperatures, which adds to the increasing solar radiation projected by the climate models for some regions. Compared to the changes in PV production, the estimated future production changes by CSP are a factor of 4 larger (Wild et al. 2017).

When regional analyses are carried out, significant discrepancies among models emerge. Multi-model means in regional models show trends in surface solar radiation of –0.60 W/m^2 per decade in 2006–2100 over Europe (Bartók et al. 2017). Solar PV supply by the end of this century should be in the range (–14%; +2%) compared to those under current climate conditions, with the largest decreases in Northern countries (Jerez et al. 2015). Therefore, despite small decreases in production expected in some parts of Europe, climate change is unlikely to threaten the European PV sector. Over southern Africa, low probability of significant changes for solar is found (Fant et al. 2016).

6.5.1.4 Ocean Energy

Ocean energy is a small portion of RE extraction and its vulnerability to climate change will not impact climate change mitigation. Wave resource is potentially affected by changes in water temperature, temperature gradients, salinity, sea level and wind patterns. There are also relationships between sea level rise and increase in tidal renewable energy (Pickering et al. 2017) and also on the optimal location for tidal energy plants (Souza 2013). Wave-tide interaction has clear implications to the combined hazard of flooding from extreme sea-level and waves (Lewis et al. 2019).

6.5.1.5 Bioenergy

Climate change can affect biomass resource potential directly, via changes in the suitable range (i.e., the area where bioenergy crops can grow) and/or changes in yield, and indirectly, through changes in land availability. Increases in CO_2 concentration increase the yield of biomass; changes in climate (e.g., temperature, precipitation, etc.) can either increase or decrease the yield and suitable range. (*high confidence*)

Climate change will shift the suitable range for bioenergy towards higher latitudes, but the net change in total suitable area is uncertain (*high confidence*). Several studies show a northward shifts in the suitable range for bioenergy in the northern hemisphere (Tuck et al. 2006; Bellarby et al. 2010; Preston et al. 2016; Barney and DiTomaso 2010; Hager et al. 2014; Conant et al. 2018; Cronin et al. 2018b; Wang et al. 2014a), but the net effect of climate on total suitable area varies by region, species, and climate model. For example, Barney and DiTomaso (Barney and DiTomaso 2010) find an increase in the total suitable area for switchgrass in the U.S. Hager et al. (2014) find decreases in the total suitable area for miscanthus globally; however, in North America, climate change can either increase or decrease suitable area depending on the climate model. Wang et al. (2014a) find decreases in suitable habitat for bioenergy in the tropics in China, but little change in overall area.

The effect of climate change on bioenergy crop yield will vary across region and feedstock (*high confidence*); however, in general, yields will decline in low latitudes (*medium confidence*) and increase in high latitudes (*low confidence*) (Haberl et al. 2010; Cosentino et al. 2012; Mbow et al. 2019; Cronin et al. 2018b; Preston et al. 2016). The average change in yield, however, varies significantly across studies, depending on the feedstock, region, and other factors. For example, (Dolan et al. 2020) find declines in switchgrass yield in the U.S., while (Kyle et al. 2014) show increases in global average yield for grassy bioenergy crops. Mbow et al. (2019) find that global average yields for corn and soybean decrease with warming. Beringer et al. (2011) find increases in net primary productivity for woody bioenergy crops. Only a few studies extend the modeling of climate change impacts on bioenergy to quantify the effect on bioenergy deployment or its implications on the energy system (Calvin et al. 2013, 2019; Thornton et al. 2017; Kyle et al. 2014). These studies find that changes in deployment are of the same sign as changes in yield; that is, if yields increase, then deployment increases.

Some of the uncertainty in the sign and magnitude of the impacts of climate change on bioenergy potential is due to uncertainties in CO_2 fertilisation (Bonjean Stanton et al. 2016; Yalew et al. 2020b; Haberl et al. 2011; Cronin et al. 2018b; Solaun and Cerdá 2019). For example, (Haberl et al. 2011) find that without CO_2 fertilisation, climate change will reduce global bioenergy potential by ~16%; with CO_2 fertilisation, climate change increases potential by 45%. However, (Dolan et al. 2020) find little effect of CO_2 fertilisation on switchgrass yield in the U.S. There is also a large uncertainty across climate and crop models in the estimate of bioenergy potential (Hager et al. 2014). For example, (Hager et al. 2014) find larger differences in the suitable range for miscanthus across climate models than across emissions scenarios.

6.5.1.6 Thermal power plants

Climate change is expected to reduce the efficiency of thermal generation and increase the risk of power plant shutdowns during droughts. Additional cooling water needs of carbon capture and storage (CCS) can increase these risks. (*high confidence*)

Climate change is expected to impact the operation of thermal power plants, including nuclear, geothermal, fossil power and bioenergy. Increasing ambient and water temperatures will mean reduced generator efficiencies due to reduced thermal efficiencies (De Sa and Al Zubaidy 2011; Cronin et al. 2018a), with 80 % of freshwater-cooled thermoelectric plants globally expected to show some reduction in usable capacity (Yalew et al. 2020b). Droughts decrease potential cooling water for thermal power plants and increase the probability of water outlet temperatures exceeding regulatory limits, leading to lower production or even shutdowns. Thermoelectric power utilisation is reported to be on average 3.8% lower during drought years (van Vliet et al. 2016c), with large decreases on usable capacity. Climate change may reduce the nuclear generation capacity available on hot days due to increasing water temperatures, with multiple power plants shutting down due to discharge water temperatures exceeding the regulatory limit under strong emissions climate change scenarios reported for Germany (Koch et al. 2014). Thermoelectric generation in Europe may decrease by up to 20% under 3°C warming, with largest impacts in the south (Tobin et al. 2018). Thermal generation is expected to decrease towards 2100 across Europe (Bonjean Stanton et al. 2016), with plants with once through cooling consistently projected to see decreased generation, whereas for closed-circuit cooling no consistent pattern of impacts can be identified. In the USA, a decrease of available thermal capacity is expected due to climate change, indicating an increased probability of power supply shortages (Miara et al. 2017). Curtailments in thermal power plant generation can also bring additional costs to the electricity market (Byers et al. 2020).

Carbon capture and storage (CCS) increases cooling water usage significantly, especially if retrofitted, with up to 50 % increase in water usage for coal-fired power plants globally, depending on the CCS technology (Rosa et al. 2020a). Climate change and increased cooling water needs due to CCS may lead to cooling water shortages in the UK by 2040 (Byers et al. 2016).

Technical solutions for mitigating the impacts of climate change on thermal power plants may be available by recalculation of cooling capacities on older plants and altering and redesigning the cooling systems (D. Westlén 2018); however, with possibly very significant costs. Modification of policies and regulation of water and heat emissions from power plants may also be used to mitigate the problems (Eisenack 2016; Mu et al. 2020). For example, plant-specific policies on water usage are reported to be more advantageous than uniform policies (Eisenack 2016; Mu et al. 2020). Improvements of water use and thermal efficiencies and use of transmission capabilities over large geographical regions to mitigate risks on individual plants are also possible mitigation options (Miara et al. 2017).

6.5.2 Impacts on Energy Consumption

Heating demand is expected to decrease and cooling demand to increase due to climate change. Recent studies project increase in net energy use. Peak load may increase more than energy consumption, and the changing spatial and temporal load patterns can impact transmission and peak-generating capacity buildout. (*high confidence*)

Energy demand will be impacted by climate change. With strong electrification of buildings' energy use foreseen, power systems are impacted by changes in heating and cooling demand. IEA projects cooling to be the fastest growing energy use in buildings (International Energy Agency (IEA 2018a). Decrease in heating demand, especially in cold regions, and increase in cooling demand, especially in warm regions, is expected (Yalew et al. 2020b). In earlier studies, the net effect on global level was expected to be small, due to compensation of decreasing heating demand by increasing cooling demand (Zhou et al. 2013; Yalew et al. 2020a). However, recent studies report larger net impacts, with the commercial and industrial sectors and strong air condition penetration driving increase in energy demand (De Cian and Sue Wing 2019; Levesque et al. 2018; van Ruijven et al. 2019; Davis and Gertler 2015; Yalew et al. 2020a). Globally, 7–17 % increase in energy consumption towards 2050 is projected (De Cian and Sue Wing 2019), depending on the climate change scenario; however, declines in residential demand drives an overall reduction in energy consumption in Europe. In addition to increased electrification, changes in fuel use are expected: residential and commercial sectors are expected to reduce their consumption of the major heating fuels, petroleum and natural gas, in the temperate regions; however, in the tropics the use of these fuels is expected to increase (De Cian and Sue Wing 2019). Electricity demand is projected to expand in every sector, while changes in natural gas demand are small and offset one another (increase for industry and decrease for households) (van Ruijven et al. 2019).

Lower demand for electricity during the cold season and a higher demand during the warm season is expected to change the seasonal load pattern (Yalew et al. 2020a; Zhang et al. 2019a). While the projected effect on European total consumption is nearly zero, the changing spatial and temporal consumption and peak load patterns can impact transmission and peak-generating capacity buildout (Wenz et al. 2017). Climate extremes are expected to impact beyond the overall change in energy consumption, with future energy peak demand expected increase more than energy demand (Yalew et al. 2020a). Total electricity consumption is expected to increase on average by 20% during summer months, while during winter it is expected to decrease on average by 6 % by the end of the century in the USA (Ralston Fonseca et al. 2019). While the average increase in consumption is modest, climate change is projected to have severe impacts on the frequency and intensity of peak electricity load in the USA (Auffhammer et al. 2017). Peak per-capita summertime load is expected to rise by 4.2%–15% by mid-century in the USA (Bartos et al. 2016). Efficient cooling technologies can be utilised in limiting the rise in cooling energy peak load (Dreyfus et al. 2020; (IEA 2018b).

6.5.3 Impacts on Power System Vulnerability

While long-term trends are important for electricity system planning, short-term effects associated with loss of power can be disruptive and lead to large economic losses along with cascading effects on health and safety. Extreme weather threatens overhead lines, supporting ICT systems, and network infrastructure. Rising sea levels may pose significant risks to coastal or riverside power system infrastructure. It is recognised that these risks compound in a complex way, for example when lightning and high winds occur simultaneously, and the corresponding impacts and severity are not fully understood.

Extreme weather and storms manifest as threat vectors to all aspects of the power system in different ways, which affect system resilience, reliability, and adequacy. These terms correspond to different aspects of power system security, but at a high level can be understood as the ability of the power system to provide power to customers as required or expected given different operational conditions.

Climate change will affect both the frequency and intensity of extreme weather events (Seneviratne et al. 2012) and the effect of climate change on power system vulnerability will depend on the degree to which climate alters the frequency and intensity these events. Climate change will affect both the frequency and intensity of extreme weather events (Seneviratne et al. 2012) and the effect of climate change on power system vulnerability will depend on the degree to which climate alters the frequency and intensity these events.

High wind speeds can shear lines through mechanical failure, or cause lines to collide with each other causing transient events. High winds can also lead to disconnections of demand on weaker networks, resulting in customer interruptions with extreme winds. Hurricane conditions can damage wind and solar PV infrastructure. In windy periods, the system may simultaneously be experiencing high demand at a time when lines are particularly at-risk from mechanical failure from wind and storm related effects. However, except for medium evidence of increases in heavy precipitation associated with tropical cyclones projected to be higher at 2°C compared to 1.5°C global warming, there is limited evidence that extreme wind events will increase in frequency in the future (*medium confidence*).

Wildfires pose a significant threat to power systems in dry periods and in arid regions (Dian et al. 2019). With climate change, the threat of wildfire to transmission systems is likely to increase, but this threat needs to be better understood and quantified so remedial action can be taken to avoid the widespread power outages and socioeconomic damage being seen in places such as California. Wildfires are likely to become more frequent (Flannigan et al. 2013) and more difficult to address given they coincide with periods of dryness and can be exacerbated by high winds, and this too compounds other emergent risks on the power system (Mitchell 2013).

Lightning can cause wildfires or common-mode faults on power systems associated with falling vegetation should it strike near power system assets such as substations or overhead lines but is more generally associated with flashovers and overloads (Balijepalli et al. 2005). Climate change can change the probability of lightning-related events, as there is physically more energy in the atmosphere (Romps et al. 2014). Given the links between wind-related faults, lightning-related faults, and wildfires, it is reasonable to conclude that the threats posed by lightning to power infrastructure are only going to increase going forward. This may manifest as transient faults due to lightning or damage caused by wildfires, both of which are likely to increase due to climate change across the globe.

Snow and icing can impact the security of overhead lines by weighing down lines beyond their mechanical limits, leading to collapse and cascading outages (Feng et al. 2015). Snow can also lead to flashovers on lines due to wet snow accumulation on insulators (Yaji et al. 2014). Global warming may mean lower risk of problematic snow and ice conditions in countries such as the UK (McColl et al. 2012). However, there is still an underlying risk of acute cold conditions such as those associated with winter storm known as the Beast from the East (Dawkins 2019).

Flooding presents as a threat to the transmission system by inundating low-lying substations, which affects both the ability to deliver power to customers connected behind the substation and the ability to route power around the power system via these stations depending on how they are connected, and restoration can be particularly challenging. Coastal flooding also poses a threat to power system infrastructure. The vulnerability of US generation plant, for example, to sea level rise is examined in detail in (Bierkandt et al. 2015). Flooding and high-water flow from run-of-river sources can also impact hydro generation through increased sediment load and potentially by restricting the ability to release water from reservoirs. Although the average levels of precipitation may fall, particularly in summer, power systems may still be vulnerable to extreme autumn and winter storm events. Furthermore, rising sea levels, as identified in (Entriken and Lordan 2012), may also pose significant risk for coastal power systems. As Fukushima (Steinhauser et al. 2014) illustrates, coastal flooding of power stations can have severe and long-lasting effects causing not only massive loss of generating capacity but severe socioeconomic and health impacts, as well. Hurricane Katrina illustrated the potentially calamitous effects of flood defense failure and such risk and its impact on the power system is difficult to quantify (Ji and Wei 2015). Given the tendency of major developed cities to be in coastal or river-adjacent areas this is a severe threat that needs to be more fully understood (Bierkandt et al. 2015; Entriken and Lordan 2012). As Fukushima (Steinhauser et al. 2014) illustrates, coastal flooding of power stations can have severe and long-lasting effects causing not only massive loss of generating capacity but severe socioeconomic and health impacts, as well. Hurricane Katrina illustrated the potentially calamitous

effects of flood defense failure and such risk and its impact on the power system is difficult to quantify (Ji and Wei 2015). Given the tendency of major developed cities to be in coastal or river-adjacent areas this is a severe threat that needs to be more fully understood.

Thermal effects influence electricity load profiles, as mentioned in Section 6.5.2. Ambient temperatures can also significantly affect the generation portfolio available, as well as potentially impacting supporting ICT infrastructure. Heat can pose a direct risk to power system equipment such as transformers. Referred to as solar heat faults (McColl et al. 2012), they occur under conditions of high temperatures and low wind speeds and can be exacerbated by the urban heat island effect. Climate change may affect system adequacy by reducing electric transmission capacity due to increasing temperatures, which can happen simultaneously with increased peak load due to increased air conditioning (Bartos et al. 2016).

Box 6.4 Impacts of Energy Systems on Local Climate

This section has described the possible consequences of climate change to the production of energy and to the transmission of electricity. However, the opposite is also possible. That is, that the rapid development of the use of energy derived from renewable sources could alter future climate.

Solar energy. The question of whether large-scale solar PV power plants can alter the local and regional climate has been addressed with observations and model simulations. In the rural environment and at the local scale, large-scale PV deployments can alter the radiative balance at the surface-atmosphere interface, they can exert certain impacts on the temperature and flow fields (Taha 2013). Measurements at an experimental site in Arizona, USA show considerable warming (3–4°C warmer at night than over wildlands) from the PV panels. In contrast, in urban settings, solar PV panels on roofs provide a cooling effect (Ma et al. 2017; Taha 2013). In the regional scale, modelling studies have also shown cooling in urban areas (0.11–0.53°C) and warming in rural areas (up to 0.27°C) (Millstein and Menon 2011). Global climate model simulations in (Hu et al. 2016) showed that solar panels alone induce regional cooling by converting incoming solar energy to electricity. However, the conversion of this electricity to heat, primarily in urban areas, increases regional and global temperatures which compensate the cooling effect. The depiction of the alteration of the surface energy balance in PV power plants is rather simplistic in these models and need to be taken with caution.

Wind Energy. Surface temperature changes in the vicinity of wind farms have been detected (Xia et al. 2019; Smith et al. 2013; Lee and Lundquist 2017; Takle et al. 2019) in the form of night-time warming. From data from field campaigns, this warming can be explained as a "suppression cooling" rather than a warming process (Takle et al. 2019). Regional and climate models have been used to describe the interactions between turbines and the atmosphere (Vautard et al. 2014). More sophisticated models confirm the local warming effect of wind farm operation, but report that the impact on the regional area is slight and occasional (Wang et al. 2019d). From a physical perspective, wind turbines alter the transport and dissipation of momentum near the surface, but do not directly impact the energy balance of the Earth as is done by the addition of greenhouse gases.

Hydropower. The potential climate impacts of hydropower concentrate on the GHG emissions from organic matter decomposition when the carbon cycle is altered by the flooding of the hydroelectric power plant reservoir (Ocko and Hamburg 2019). However, it is pointed out that these impacts vary greatly among facilities and over time.

6.6 Key Characteristics of Net-Zero CO2 Energy Systems

6.6.1 What is a Net-Zero Energy System?

Limiting warming to 1.5 °C or well below 2 °C, ultimately requires that CO_2 emissions from the energy sector be reduced to near zero or even below zero.). Policies, technologies, behaviors, investments, and other actions today will determine the speed at which countries are able to transform their energy systems to those that emit little or no CO_2 or that might even remove emissions from the atmosphere. An understanding of these future energy systems is valuable to chart a course toward them over the coming decades.

This section synthesises current understanding of net-zero energy systems. The subsequent section (Section 6.7) discusses pathways toward and beyond these net-zero energy futures. A useful starting point is to consider energy systems associated with net-zero CO_2 emissions across the whole economy. The net zero, economy-wide CO_2 framing has become increasingly salient in long-term planning documents. Discussions surrounding efforts to limit warming are now frequently communicated in terms of the point in time at which net anthropogenic CO_2 emissions reach zero, accompanied by substantial reductions in non-CO_2 emissions (IPCC 2018). This economy-wide CO_2 goal also appears in many government and company decarbonisation strategies, though it is used in a variety of ways (Levin et al. 2020). Most existing carbon-neutrality commitments from countries and subnational jurisdictions aim for economies with very low emissions but are non-zero, as offsets, carbon dioxide removal (CDR) methods, and/or land sink assumptions are used to achieve net-zero goals.

A precise description of a net-zero energy system is complicated by the fact that different scenarios associate different future CO_2 emissions to the energy system, even at the point when economy-wide CO_2 emissions reach net zero, as well as the dependence of system configuration on population growth and technological change (Rogelj et al. 2015a). The energy system is not the only source or sink of CO_2 emissions. Terrestrial systems may store or emit carbon, and engineered CDR options can be used to store CO_2, relieving pressure on the energy system (see Chapter 3). The location of engineered CDR is also ambiguous, as it might be deployed within or outside of the energy sector (Figure 6.21), and many CDR options, such as direct air capture, would be important energy users even though they do not provide energy services. In other cases, if CDR methods are deployed outside of the energy system (e.g., net negative agriculture, forestry, and land use CO_2 emissions), it is possible for the energy system to still emit CO_2 even while economy-wide emissions are zero or below. When global energy and industrial CO_2 emissions reach net zero, the space remaining for fossil energy is determined by the degree of negative emissions deployed, which can come from options such as bioenergy with carbon capture and sequestration (BECCS) and direct air capture (DAC) (Figure 6.21).

For the purposes of the assessment in this section, we focus on energy systems that produce net-zero CO_2 emissions. While these systems may not correspond directly to the point at which overall economy-wide CO_2 emissions reach net zero, they are nonetheless a useful benchmark for planning. Note that the focus here is on energy systems with net-zero CO_2 emissions from fossil fuels and industrial processes. It is anticipated that important efforts will be made to reduce emissions of non-CO_2 emissions as well, but this aspect of net-zero energy systems is not discussed in this section. Also note that, when emissions reach net zero globally, the energy sector in many countries does not reach net zero levels, as illustrated in the regional scenario results in Figure 6.25.

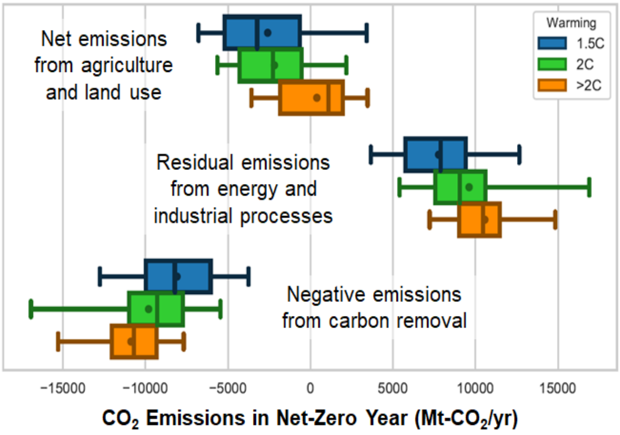


Figure 6.21 Residual and negative emissions when global energy and industrial CO_2 emissions reach net-zero. Residual and negative emissions in net-zero scenarios show global differences across warming levels. DAC is included in energy sector emissions. Points represent different models and scenarios from the IPCC "Global Warming of 1.5 °C" report database (Huppmann et al. 2018). In each case, the boxes show the 25th to 75th percentile ranges for the 177 scenarios, and whiskers show the 5th and 95th percentiles. Lines and circles within the boxes denote the median and mean values, respectively.

6.6.2 Configurations of Net-zero Energy Systems

Configurations of net-zero energy systems will vary by region but are likely to share several common characteristics (*high confidence*). Net-zero energy systems could involve a range of configurations, which entail trade-offs across economic, environmental, and social dimensions (Davis et al. 2018a). Many socioeconomic, policy, and market uncertainties will also influence the configuration of net-zero energy systems (Van Vuuren et al. 2018 Krey et al. 2019；Bistline et al. 2019；Smith et al. 2016). As discussed in Section 6.6.5, there are many reasons that countries might focus on one system configuration versus another, including cost, resource endowments, related industrial bases, existing infrastructure, geography, governance, public acceptance, and other policy priorities.

Types of net-zero energy systems are still emerging in modeling studies and have not been clearly detailed in most country-specific pledges or in the detailed systems modeling literature. Reports associated with net-zero economy-wide targets for countries and subnational entities typically do not provide detailed roadmaps or modeling but discuss high-level guiding principles, though more detailed studies are emerging (e.g., Capros et al. 2019. Analysis has focused on identifying potential decarbonisation technologies and pathways for different sectors, enumerating opportunities and barriers for each, their costs, highlighting robust insights, and characterising key uncertainties (Hepburn et al. 2019; Davis et al. 2018). The literature on net-zero energy systems is limited in a few respects. On the one hand, there is a robust integrated assessment literature that provides characterisations of these systems in very broad strokes (AR6 database), offering internally consistent global scenarios to link global warming targets to regional/national goals through their global scope and longer time horizons. All integrated assessment scenarios that pass through net zero energy sector CO_2 emissions provide high-level characterisations of those systems. However, because these characterisations operate at a high level, they do not consider the complexities of the many system interactions, infrastructure needs, policy implementations, associated scaling challenges, and societal factors that could ultimately influence what system might be most appropriate for any country. While valuable in highlighting key themes, global integrated assessment models do not have the temporal, spatial, technological, regulatory, and societal details that are necessary to more concretely identify regional, national, or local pathways. Literature that takes a more granular view is more limited (e.g., Davis et al. 2018), although there is an increasingly abundant literature on particular aspects of potential net-zero energy systems, most notably decarbonised electricity systems (see Section 6.6.2.2), and cross-sector linkages (see

Section 6.6.2.6). While the literature on net-zero energy systems is diverse, it is also true that a number of common characteristics emerge from across the space of existing literature (Figure 6.22). We focus on those common characteristics in the remainder of this subsection.

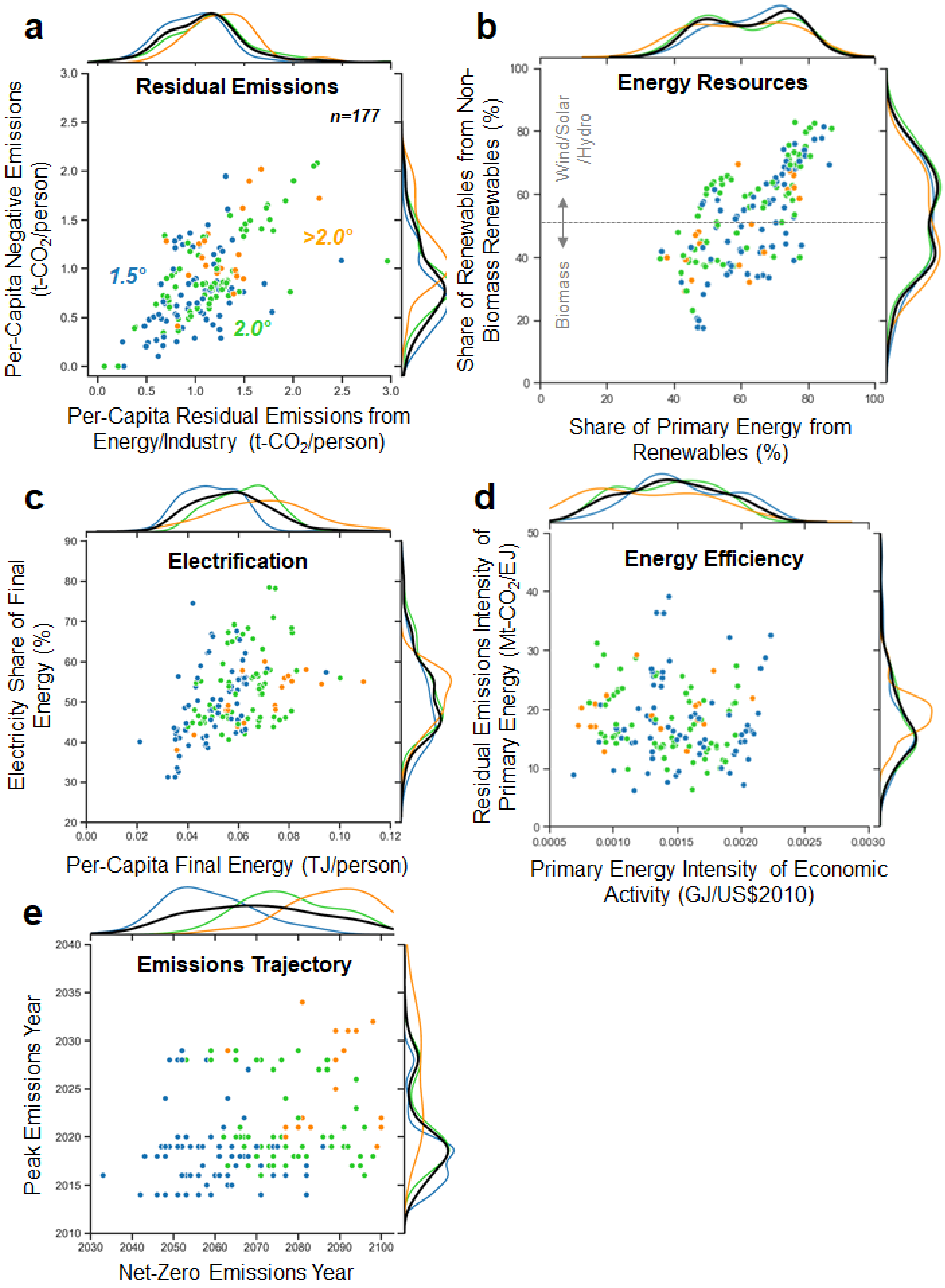


Figure 6.22 Characteristics of global net-zero energy systems. Scenarios reaching net-zero emissions show differences in residual emissions and carbon removal (a), energy resources (b), electrification (c), energy efficiency (as measured here by energy/GDP) (d), and emissions trajectory (e), particularly with respect to warming levels (blue = <1.5˚C, green = <2.0˚C, orange = >2.0˚C). Points represent individual scenarios, with probability density distributions shown along each axis for each warming level (colors corresponding to warming levels) and for all scenarios (black). Points represent different models and scenarios from the IPCC "Global Warming of 1.5 °C" report database (Huppmann et al. 2018).

Box 6.5 Common Characteristics of Net-zero Energy Systems

- *Limited and targeted use of fossil fuels*
- *Zero or negative CO_2 emissions from electricity*
- *Widespread electrification of end uses*
- *Alternative fuels in hard-to-decarbonise sectors*
- *More efficient use of energy than today*
- *Greater reliance on integrated energy system approaches*
- *Use of carbon dioxide removal (CDR) technologies.*

6.6.2.1 Limited and/or Targeted Use of Fossil Fuels

Net-zero energy systems will use far less fossil fuels than today (*high confidence*). The precise quantity of fossil fuels will largely depend upon the relative costs of such fuels, electrification, and CDR in the energy system (*high confidence*). All of these are affected by regional differences in resources (e.g., McGlade and Ekins 2015b), demand for energy services, and climate and energy policies. Fossil fuel use may persist, for example, if and where the costs of such fuels and the compensating carbon management (e.g., CDR, CCUS) are less than non-fossil energy. For most applications, however, it is likely that electrification (e.g., McCollum et al. 2014; Madeddu et al. 2020; Zhang and Fujimori 2019) or use of non-fossil sources of fuels (e.g., Zeman and Keith 2008; Graves et al. 2011; Hänggi et al. 2019) will prove the be the cheapest options. Residual demand for fossil fuels is likely to predominantly be petroleum and gas given their high energy density (Davis et al. 2018b); demand for coal in net-zero energy systems is likely to be very low (Luderer et al. 2018; Jakob et al. 2020)(*high confidence*).

There is considerable flexibility regarding the overall quantity of liquid and gaseous fuels that will be required in net-zero energy systems (*high confidence*) (Figure 6.22). This will be determined by the relative value of such fuels as compared to systems which rely more or less heavily on zero-emissions electricity. In turn, the share of any fuels that are fossil or fossil-derived is uncertain, and will depend on the feasibility of CCUS and CDR technologies and long-term sequestration as compared to carbon-neutral fuels. Moreover, to the extent that physical, biological, and/or socio-political limit the availability of CDR (e.g., (Smith et al. 2015; Field and Mach 2017), carbon management efforts may prioritise residual emissions related to land use and other non-energy sources.

6.6.2.2 Zero or Negative CO2 Emissions from Electricity

Net-zero energy systems will rely on decarbonised or net-negative CO_2 emissions electricity systems, due to the many lower-cost options for producing zero-carbon electricity and the important role of end-use electrification in decarbonising other sectors (*high confidence*).

There are many possible configurations and technologies for zero- or net-negative-emissions power systems (*high confidence*). These systems could entail a mix of variable renewables, dispatchable renewables (e.g., biomass, hydropower), other firm dispatchable ("on-demand") low-carbon generation (e.g., nuclear, CCS-equipped capacity), energy storage, transmission, carbon removal technologies (e.g., BECCS, DAC), and demand management (Bistline et al. 2018; Jenkins et al. 2018; Luderer et al. 2017). Marginal abatement costs increase as systems approach 100 percent decarbonisation, which means that a range of technologies might be cost-effective in reaching CO_2 emissions targets and broader sustainability goals while lowering costs (Jayadev et al. 2020; Bistline et al. 2018; Mileva et al. 2016; Sepulveda et al. 2018). Key factors influencing the technology mix could include relative costs and system benefits, local resource bases, infrastructure availability, regional integration and trade, co-benefits, societal preferences and other policy priorities, all of which vary by country and region (see Section 6.6.4). Many of these factors depend on when the net-zero point is reached, which can vary significantly Figure 6.22 Characteristics of global net-zero energy systems. Scenarios reaching net-zero emissions show differences in residual emissions and carbon removal (a), energy resources (b), electrification (c), energy efficiency (as measured here by energy/GDP) (d), and emissions trajectory (e), particularly with respect to warming levels (blue = <1.5˚C, green = <2.0˚C, orange = >2.0˚C). Points represent individual scenarios, with probability density distributions shown along each axis for each warming level (colors corresponding to warming levels) and for all scenarios (black). Points represent different models and scenarios from the IPCC "Global Warming of 1.5 °C" report database (Huppmann et al. 2018). Figure 6.22 panel e).

Based on their increasing economic competitiveness, variable renewable energy, especially wind and solar power, will likely comprise large shares of many regional generation mixes (*high confidence*) (Figure 6.22). While wind and solar will likely be prominent electricity sources, this does not imply that 100% renewable energy systems will be pursued under all circumstances, since economic and operational challenges increase nonlinearly as shares approach 100 percent (Box 6.6) (Bistline and Young 2019; Shaner et al. 2018; Frew et al. 2016; Imelda et al. 2018). Real-world experience is accumulating with planning and operating regional power systems with high instantaneous and annual shares of renewable generation. But debates continue about how much wind and solar might be optimal for different systems and the cost-effectiveness of different mechanisms for managing variability (See Box 6.6). Either dispatchable generation or seasonal energy storage (alongside other balancing resources discussed in Box 6.6) will be needed to ensure reliability and resource adequacy with high percentages of wind and solar (Jenkins et al. 2018; Dowling et al. 2020), though each option involves uncertainty about costs, timing, and public acceptance (Albertus et al. 2020).

Power systems require a range of different functional roles – for example, providing energy, capacity, or ancillary services. This is another reason that a range of different types of generation, energy storage, and transmission resources may be deployed in these systems. There are many options for each of these roles, each with their strengths and weaknesses (see Section 6.4), and deployment of these resources will be influenced by the evolution of technological costs, system benefits, and local resources (Veers et al. 2019; Mai et al. 2018; Bistline et al. 2018; Hirth 2015; Fell and Linn 2013)

System management is critical for zero- or negative-emissions power systems and should be considered in planning them and integrating with broader net-zero energy systems. Maintaining reliability will increasingly entail system planning and operations that account for characteristics of supply- and demand-side resources (Hu et al. 2018). Coordinated planning and operations will likely become more prevalent across portions of the power system (e.g., integrated generation, transmission, and distribution planning), across sectors, and across geographies (Bistline and Young 2019; Chan et al. 2018; Konstantelos et al. 2017; EPRI 2018).

Energy storage will be increasingly important in net-zero energy systems, especially in systems with high variable renewable energy (*high confidence*). Deployment of energy storage will vary based on the system benefits and values of different options (Arbabzadeh et al. 2019; Denholm and Mai 2019; Denholm and Mai 2019). Diurnal storage options like lithium-ion batteries have different value than storing and discharging electricity over longer periods through long-duration energy storage with less frequent cycling, which require different technologies, supporting policies, and business models (Gallo et al. 2016; Albertus et al. 2020; Blanco and Faaij 2017) (see Section 6.4). The value of energy storage varies with the level of deployment and on the competitiveness of economic complements such as variable renewables (Bistline and Young 2020; Mileva et al. 2016) and substitutes such as flexible demand (Brown et al. 2018; Merrick et al. 2018), transmission (Merrick et al. 2018; Brown et al. 2018; Bistline and Young 2019b; Schlachtberger et al. 2017), trade (Bistline et al. 2020), dispatchable generators (Hittinger and Lueken 2015; Gils et al. 2017; Arbabzadeh et al. 2019), DAC (Daggash et al. 2019), and efficiencies in system operations (Tuohy et al. 2015).

The approach to hard-to-decarbonise sectors could impact power sector planning, and the role of some technologies (e.g., hydrogen, batteries, CCUS) could depend on deployment in other sectors. CCUS offers opportunities for negative emissions when fueled with syngas or biomass containing carbon captured from the atmosphere (Hepburn et al. 2019); however, concerns about lifecycle environmental impacts, uncertain costs, and public acceptance are potential barriers to widespread deployment (Section 6.4.2.5). It is unclear whether negative emissions technologies like BECCS will be included in the electricity mix to offset continued emissions in other parts of the energy system or beyond (Luderer et al. 2018; Bauer et al. 2018; Mac Dowell et al. 2017). Hard-to-decarbonise applications may also rely on power-to-X electricity conversion to create low-emissions synthetic fuels (see Section 6.6.2.6), which could impact power system planning and operations. Additionally, if DAC technologies are used, electricity and heat requirements to operate DAC could impact power system investments and operations (Realmonte et al. 2019).

High-fidelity models and analyses are needed to assess the economic and environmental characteristics and the feasibility, of net-zero or negative emissions electricity systems(*high confidence*) (Bistline and Blanford 2020; Blanford et al. 2018). Evaluating the competitiveness of power sector technologies requires temporal, spatial, and technological detail that are represented with higher fidelity in national/regional electric sector and energy systems models than in global integrated assessment models (Bistline, et al., 2020; Helistoe et al. 2019; Collins et al. 2017; Cole et al. 2017; Santen et al. 2017).

Box 6.6 100% Renewables in Net-Zero Energy Systems

The decreasing cost and increasing performance of renewables, along with their lack of fuel and lower waste, has generated interest in the feasibility of providing all, or nearly all, energy services with renewables. Renewables include wind power, solar power, hydroelectric power, bioenergy, geothermal energy, tidal power, and ocean power.

Although there are debates about how much wind and solar is economic under different conditions and which mechanisms would be feasible to facilitate integration, it is technically feasible to use very high renewables shares (e.g., above 75% of annual regional generation) to meet hourly electricity demand under a range of conditions (*high confidence*). An emerging question is whether it is feasible to produce all electricity using renewable sources. There are currently many grids with high renewable shares and large anticipated roles for variable renewables, primarily wind and solar (see Section 6.4), in future low-carbon power systems). High wind and solar penetration involves technical and economic challenges due to their unique characteristics such as spatial and temporal variability, short- and long-term uncertainty, and non-synchronous generation (Cole et al. 2017), which become increasingly important as renewable shares approach 100%. To manage these issues, studies indicate roles for larger installed system capacity, including intentional curtailment, substantial amounts of energy storage, expanded transmission and balancing area size, and increased flexibility in both generation and load responsiveness, among other approaches (Jenkins et al. 2018; Mai et al. 2018; Milligan et al. 2015). An increasingly large set of studies examines the feasibility of high renewable penetration and economic drivers under different policy, technology, and market scenarios (Bistline and Young 2019; Hansen et al. 2019; Jenkins et al. 2018; Cochran et al. 2014).

There are many balancing options in electricity systems with very high renewable shares including:

- **Energy storage:** Energy storage technologies like batteries, pumped hydro, and hydrogen can provide a range of system services (Balducci et al. 2018; Bistline, et al. 2020). Lithium-ion batteries have received attention as costs fall and installations increase, but very high renewable shares typically entail either dispatchable generation or seasonal storage (Arbabzadeh et al. 2019; Matsuo et al. 2020; Jenkins et al. 2018). Energy storage technologies are part of a broad set of options (including synchronous condensers, demand-side measures, and even inverter-based technologies themselves) for providing grid services (EPRI 2019; Castillo and Gayme 2014).
- **Transmission and trade:** To balance differences in resource availability, studies of high renewable systems also typically entail investments in transmission capacity (Zappa et al. 2019; Pleßmann and Blechinger 2017; Macdonald et al. 2016; Mai and Et al 2014) and changes in trade (Bistline et al. 2020; Abrell and Rausch 2016). These increases are often accompanied by expanded balancing regions to take advantage of geographical smoothing.
- **Dispatchable ("on-demand") generation:** Dispatchable generation could include flexible fossil units with lower minimum load levels (Bistline et al. 2019; Denholm et al. 2018); renewables like hydropower, geothermal, or biomass (Hirth 2016); or flexible nuclear (Jenkins et al. 2018a). The composition depends on costs and other policy goals, though in all cases, capacity factors are low for these resources (Mills et al. 2020).
- **Demand management:** Many low-emitting and high-renewables systems also utilise increased load flexibility in the forms of energy efficiency, demand response, demand flexibility, and sector coupling (Imelda et al. 2018; Hale 2017; Merrick et al. 2018; Brown et al. 2018; Ma et al. 2013).
- **Sector coupling:** Sector coupling includes increased end-use electrification and power-to-X electricity conversion pathways (see Sections 6.4.3, 6.4.4, and 6.4.2.6).

Deployment of integration options depends on their relative costs and value, as well as regulations and power market design. There is considerable uncertainty about future technology costs, performance, availability, scalability, and public acceptance (Kondziella and Bruckner 2016; Bistline and Young 2019a). Deploying balancing resources likely requires operational, market design, and other institutional changes, as well as technological changes in some cases (Cochran et al. 2014). Mixes will differ based on resources, system size, flexibility, and whether grids are isolated or interconnected.

Although there are no inherent upper bounds on renewable electricity penetration, the economic value of additional wind and solar capacity typically decreases as their penetration rises due to lower resource value and integration costs, creating economic challenges at higher deployment levels (Wiser et al. 2017; Gowrisankaran et al. 2016; Hirth 2013; Ueckerdt et al. 2013). The integration options above, as well as changes to market design, can mitigate these challenges but likely will not solve them, especially since these technologies can exhibit declining value themselves (Denholm and Mai 2019; Bistline 2017; De Sisternes et al. 2016) and may be complements or substitutes to each other. Additionally, decarbonisation approaches outside of the electric sector could have important implications for power sector planning and renewable integration strategies (Section 6.4.2.6).

100% renewable energy systems (not only the power sector) will likely not be cost-minimising solutions and raise a range of technological, regulatory, market, and operational challenges (*high confidence*). Beyond electricity, a broader question emerges regarding the attractiveness and variability of supplying all energy, and not just electricity, with renewables (Figure 6.22). Integrated assessment and energy systems research suggest large roles for variable renewables and energy storage, but energy and electricity shares are far from 100%, even with stringent emissions reductions targets and optimistic assumptions about future cost reductions (SR15 database; Huntington et al. 2020; Jenkins et al. 2018b; Bauer et al. 2018; Bistline et al. 2018). Very high renewable and electrification energy systems entail technical and economic challenges as shares approach 100%. Scenarios with 100% renewable energy systems are an emerging subset in the decarbonisation literature, especially at regional levels (Hansen et al. 2019). Many studies focus on electrification as an end-use decarbonisation strategy and do not consider significant contributions from biofuels or other renewable fuels (Bauer et al. 2018a). These studies typically assume a constrained set of available technologies to demonstrate the technical feasibility of very high renewable systems and are not optimising to find least-cost, technology-neutral decarbonisation pathways (Jenkins et al. 2018b) . Deep decarbonisation analyses, including multi-model comparison studies with detailed models of energy system investments and operations, often indicate large roles for variable renewables, but least-cost pathways for meeting emissions reduction targets rarely suggest near 100% renewables (Figure 6.22) unless optimistic assumptions about integration challenges are combined with pessimistic assumptions about alternatives (Jenkins et al. 2018b; Bistline et al. 2018). The 100% renewables literature assumes (implicitly or explicitly) that factors beyond cost and emissions attributes will drive portfolio selection. Although many studies find 100% renewable systems technically conceivable, economic and operational challenges increase nonlinearly as shares approach 100 percent (Bistline and Young 2019a; Imelda et al. 2018; Shaner et al. 2018; Bistline 2017; Frew et al. 2016). In addition to variable renewables, studies broadly agree that including additional low-, zero-, and negative-CO_2 technologies – including dispatchable renewables (e.g., biomass, geothermal, hydropower), other firm dispatchable ("on-demand") low-carbon generation (e.g., nuclear, hydrogen, CCS-equipped capacity), energy storage, transmission, carbon removal technologies (e.g., BECCS, DAC), and demand management – can lower the cost of decarbonisation even with very high shares of wind and solar, but there is disagreement about the magnitude of cost savings from larger portfolios, which depends on context- and scenario-specific assumptions about technologies, markets, and policies (Zappa et al. 2019; Bistline and Young 2019a; Sepulveda et al. 2018; Hirth 2015; Matsuo et al. 2020; Bistline and Blanford 2020).

6.6.2.3 *Widespread Electrification of End Uses*

Net-zero energy systems will rely more heavily on increased use of electricity (electrification) in end uses (*high confidence*). The literature on net-zero energy systems almost universally calls for increased electrification as a core decarbonisation strategy (Williams et al. 2012; Sugiyama 2012; Williams et al. 2014; Rogelj et al. 2015; Sachs et al. 2016; Kriegler et al. 2014; Sven et al. 2018; Luderer et al. 2018; Schreyer et al. 2020). At least 30% of the global final energy needs are expected to be served by electricity, with some estimates suggesting upwards of 80% of total energy use being electrified (Figure 6.22, panel c). Increased electrification for a broad set of end-uses is possible, and especially valuable in net-zero energy systems due to the relative ease of decarbonising electricity generation or creating net-negative emissions in electricity generation (see section 6.6.2.2). Flexible electric loads (electric vehicles, smart appliances) are in turn expected to facilitate grid decarbonisation by mitigating renewable integration challenges.

Several end-uses such as passenger transportation (light-duty electric vehicles, two and three wheelers, buses, rail) as well as building energy uses (lighting, cooling) are assumed to be electrified in virtually all net-zero energy systems (*high confidence*). Variations largely result from differences in the ability and cost-competitiveness of electricity to serve other end uses such as non-rail freight transport, aviation, and heavy industry (McCollum et al. 2014; Breyer et al. 2019; Bataille et al. 2016; EPRI 2018;) also see Section 6.6.2.4), especially relative to biofuels and hydrogen ('low carbon fuels') (Sachs et al.

2016; Rockström et al. 2017; McCollum et al. 2014), the prospects for which are still quite uncertain (see Section 6.4).The emergence of negative emissions technologies and the extent to which they allow for residual emissions as an alternative to electrification will also affect the overall share of energy served by electricity (see Section 6.6.2.7).

Regions endowed with cheap and plentiful low-carbon electricity resources (wind, solar, hydropower) will favor electrification, while those with substantial bioenergy production or availability of other liquid fuels might put less emphasis on electrification, particularly in hard-to-electrify end-uses (*medium confidence*). For example, among a group of Latin American countries, relative assumptions about liquid fuels and electricity result in an electrification range of 28% to 82% for achieving a net-zero energy system (Bataille et al. 2020). Similarly, the level of penetration of biofuels that can substitute for electrification will depend on regional circumstances such as land-use constraints, competition with food, and sustainability of biomass production (see Section 6.6.4).

Electrification of most buildings services, with the possible exception of space heating in extreme climates, is expected in net-zero energy systems (*high confidence*) (See Buildings chapter). Space cooling and water heating are expected to be largely electrified. Building electrification will lower emissions both through reduced thermal requirements and higher efficiencies, and the role of heat pumps is significant (Mathiesen et al. 2015; Rissman et al.2020; Sven et al. 2018). The level of electrification will depend on the tradeoffs between household level heat pumps versus district heating options (Mathiesen et al. 2015; Brown et al. 2018), as well as the cost and performance of heat pumps in more extreme climates and grid infrastructure (EPRI 2018; Waite and Modi 2020).

A significant share of transportation, especially road transportation, is expected to be electrified globally in net-zero energy systems (*high confidence*). In road-transportation, two-three wheelers, light-duty vehicles (LDVs), and buses, are especially amenable to electrification, with more than half of passenger LDVs expected to be electrified globally in net-zero energy systems (*medium confidence*) (Fulton et al; 2015; Bataille et al. 2020; Sven et al. 2018; Khalili et al. 2019). Due to increasing demand for road freight transport, emissions reductions without modal shifts will be challenging (Carrara and Longden 2017; Sven et al. 2018; Muratori et al. 2017). Due to the relative ease of rail electrification, almost complete electrification of rail and shifting air and truck freight to rail is expected to play a role in achieving net zero emissions (Rockström et al. 2017; Fulton et al. 2015; Sven et al. 2018; Khalili et al. 2019). The overall levels of modal shifts and electrification will depend on local factors such as infrastructure availability and location accessibility. Due to the challenges associated with electrification of some transport modes, some studies show residual emissions associated with the freight sector that are offset through negative emissions technologies (Muratori et al. 2017c), or reliance on low and zero-carbon fuels instead of electrification. Long-haul trucks, large ships and aircrafts are expected to be harder to switch to electrification, so the expected share of electricity serving these end-uses directly will be relatively low absent technological breakthroughs (Fulton et al. 2015; Mathiesen et al. 2015).

A non-trivial number of industry applications could be electrified as a part of a net-zero energy system; however, direct electrification of heavy industry applications such as cement, primary steel manufacturing, and chemical feedstocks is expected to be challenging (*medium confidence*) (Davis et al. 2018; Madeddu et al. 2020), also see Section 6.6.2.4). Electrification of process and boiler heating in industrial facilities is expected to play an early role in decarbonisation efforts for industry. Cement and concrete production can be made less emissions intensive through the use of electrified cement kilns; similarly, emissions associated with steel production can be reduced through the use of an electric arc furnace (EAF) powered by decarbonised electricity (Rissman et al., 2020). Electricity can also be used to replace thermal heat such as resistive heating, electric arc furnaces and laser sintering (Rissman et al., 2020; Madeddu et al. 2020). Based on a study of the European industrial sector, as high as 60% of the energy-end use in industry could be met with direct electrification using existing and emerging technologies (Madeddu et al. 2020).The total level of industry electrification for different regions will depend on the economics and availability of alternative emissions mitigation strategies such as carbon neutral fuels and carbon capture and sequestration (Davis et al. 2018; Madeddu et al. 2020).

6.6.2.4 Alternative Fuels in Hard-to-Decarbonise Sectors

Net-zero energy systems will need to rely on alternative fuels – notably hydrogen or biofuels – in several sectors that are not amenable to electricity and otherwise hard to decarbonise (*medium confidence*). Useful hydrocarbons (e.g., methane, petroleum, methanol), hydrogen, ammonia, or alcohols can be produced with net-zero CO_2 emissions and without fossil fuel inputs. For example, liquid hydrocarbons can be synthesised via hydrogenation of non-fossil carbon by processes such as Fischer-Tropsch (Mac Dowell et al. 2017) or by conversion of biomass (Tilman et al. 2009). The resulting energy-dense fuels can serve applications that are difficult to electrify, such as long-distance freight, long-haul aviation, and high-temperature industrial heating (Davis et al. 2018; NAS 2016). But it is not clear if and when the combined costs of obtaining necessary feedstocks and producing these fuels without fossil inputs will be less than continuing to use fossil fuels and managing the related carbon.

CO_2 emissions from some energy services are expected to be particularly difficult to cost-effectively avoid, among them aviation; long-distance freight by ships, trains, and trucks; process emissions from cement and steel production; high-temperature heat (e.g., >1000°C); and electricity reliability in systems with high penetration of variable renewable energy sources (Davis et al. 2018; Luderer et al. 2018; (Chiaramonti 2019; Sepulveda et al. 2018; Bataille 2020; Rissman et al., 2020) The literature focused on these services and sectors is quite limited, however, and provides minimal guidance on the most promising or attractive technological options and systems for avoiding these sectors' emissions. Moreover, many of the technologies mentioned in the literature are prohibitively expensive, exist only at an early stage, or are subject to much broader concerns about sustainability (e.g., biofuels) (Davis et al. 2018a).

Liquid biofuels today supply about 4% of transportation energy worldwide, mostly as ethanol from grain and sugar cane and biodiesel from oil seeds and waste oils (Davis et al. 2018a). These biofuels could conceivably be targeted to difficult-to-decarbonise sectors, but face substantial challenges related to their life-cycle carbon emissions, cost, and further scalability (Tilman et al. 2009; Staples et al. 2018, Section 6.4.2.6). The extent to which biomass will supply liquid fuels in a future net-zero energy system will thus depend on advances in conversion technology that enable use of feedstocks such as woody crops, agricultural residues, algae, and wastes, as well as competing demands for bioenergy and land, the feasibility of other sources of carbon-neutral fuels, and integration of bioenergy production with other objectives, including CDR, economic development, food security, ecological conservation, and air quality (Lynd 2017; Laurens 2017; Williams and Laurens 2010; Bauer et al. 2018; Fargione 2010; Creutzig et al. 2015; Bauer et al. 2018b; Muratori et al. 2020b, Section 6.4.2.6).

Costs are the main barrier to synthetic hydrocarbons (*high confidence*). Hydrogen is a constituent of such hydrocarbons (as well as in ammonia and alcohols) (Section 6.4.5.1). Today, most hydrogen is supplied by steam reformation of fossil methane (CH_4 into CO_2 and H_2) at a cost of USD 1.30-1.50 per kg (Izquierdo et al. 2012) Non-fossil hydrogen can be obtained by electrolysis of water, but the cheapest and most mature electrolysis technology today uses alkaline electrolytes with metal catalysts to produce hydrogen at a cost of roughly USD 5.50/kg H_2 (assuming electricity costs of U.S. USD 0.07/kWh and 75% utilisation rates) (Graves et al. 2011). At this cost for electrolytic hydrogen, the minimum price would be USD 1.70/liter of diesel equivalent (or USD 6.50/gallon and USD 50 per GJ, assuming carbon feedstock costs of USD 100 per ton of CO_2 and low process costs of USD 0.05/liter or USD 1.50 per GJ) (Graves et al. 2011). R&D efforts are targeting 60-80% reductions in the costs of less mature but promising technologies, such as high-temperature solid oxide or molten carbonate fuel cells, or thermochemical water splitting (DOE 2017; Schmidt et al. 2017; DOE 2018; Saba et al. 2018; Kuckshinrichs et al. 2017). Technologies capable of producing hydrogen directly from water and sunlight (photoelectrochemical cells or photocatalysts) are also under development, but still at an early stage (Nielander et al. 2015). High hydrogen production efficiencies have been demonstrated, but costs, capacity factors, and lifetimes need to be improved in order to make such technologies feasible for carbon-neutral fuel production at scale (McKone et al. 2014).

The carbon contained in carbon-neutral hydrocarbons must also have been removed from the atmosphere either through DAC or, in the case of biofuels, by photosynthesis (which could include CO_2 captured from the exhaust of biomass or biogas combustion) (Zeman and Keith 2008; Graves et al. 2011). A number of different groups are now developing DAC technologies, targeting costs of USD 100 per ton of CO_2 or less (Darton and Yang 2018; Keith et al. 2018; Fasihi et al. 2019).

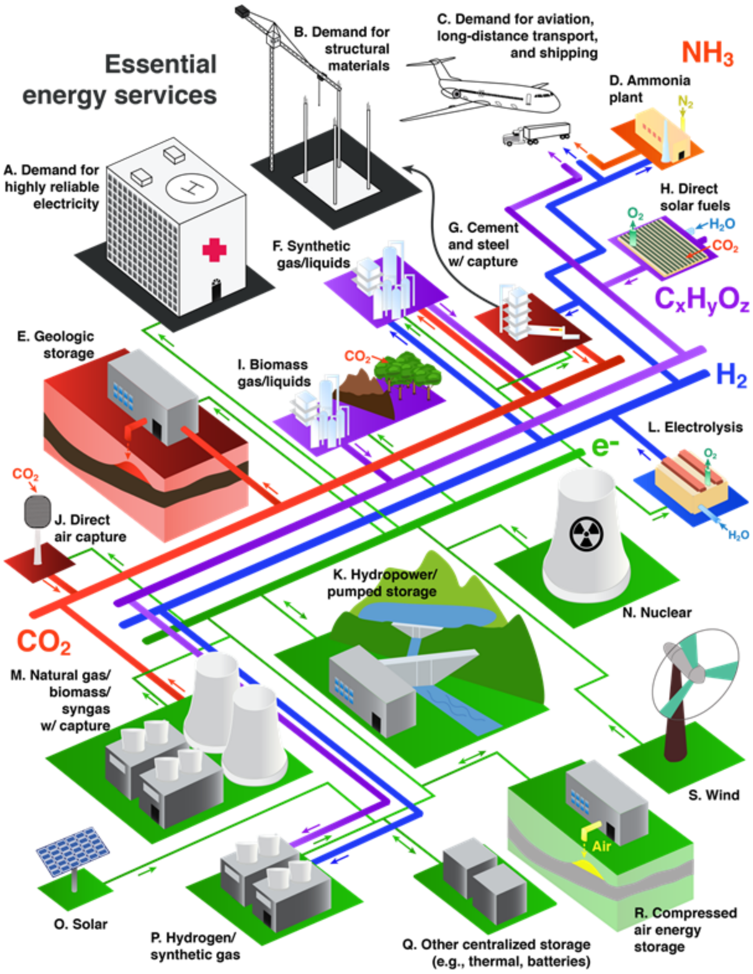


Figure 6.23 Energy System from Davis et al. as an example of methods to address hard-to-electrify sectors. (Source: Davis et al. 2018)

Box 6.7 The Hydrogen Economy

The phrase “hydrogen economy” is often used to describe future energy systems in which hydrogen (Section 6.4) plays a prominent role. These energy systems would not use hydrogen in all or most energy to end uses; they would use hydrogen as a complement to other energy carriers where hydrogen might have particular advantages. Hydrogen-based fuel-cells could fuel heavy-duty vehicles (e.g. buses, trains and lorries) and potentially lighter vehicles for longer-range journeys (Kendall and Pollet 2012; European Policy Solutions 2018; Office for Low Emission Vehicles 2018; UK Department of Transport

2017). Hydrogen could replace natural gas-based electricity generation (IRENA 2019d), and it could provide long-term storage to support high-penetration wind and solar power hydrogen could enable trading and storage of electricity between different regions to overcome seasonal or production differences. Hydrogen also be used for heating, seasonal energy storage, transport of energy over long distances, and industrial processes (e.g., as feedstock for the chemical industry or direct reduction of iron ore (Vogl et al. 2018). Countries may be able to export hydrogen or hydrogen-based fuels to better support global mitigation efforts.

Hydrogen production costs have historically been prohibitive. However, recent developments and improvements in hydrogen production technologies in terms of efficiency and capital costs (e.g. SMR) (Committee on Climate Change 2018), and emergence of technologies (e.g., mainly electrolysers; SOEC) for hydrogen production are becoming more competitive (Schmidt et al. 2017b). These technological changes, along with decreasing costs of renewable power, are increasing the viability of hydrogen. For example, electrolysis from offshore wind could reduce costs an additional 60% by 2030 (Hydrogen Council 2020).

In order for hydrogen to support decarbonisation, it will need to be produced from zero-carbon energy sources or, if not, offset by carbon sequestration. “Blue hydrogen” would be produced from natural gas through the process of autothermal reforming (ATR) or steam methane reforming (SMR), combined with carbon capture and storage (CCS) technology that would absorb most of the resulting CO_2 (80-90%). “Green hydrogren” would be produced by the electrolysis of water via low-temperature electrolysis (LTE) or high-temperature electrolysis (HTE) processes, using renewable or other low-carbon electricity sources. Hydrogen can also be produced through gasification of biomass with CCS (BECCS), leading to negative carbon emissions (IRENA 2019d).

Hydrogen faces a number of barriers and challenges. The potential role of hydrogen in future energy systems depends in large part on its competitiveness and the infrastructural needs to deploy it at relevant scales (IRENA 2019d; DENA 2017). Global deployment of hydrogen (e.g. Muratori et al. 2018; Gumber and Gurumoorthy 2018) through the existing gas infrastructures (e.g., within a country) is not feasible. Beside physical barriers, such as steel embrittlement and degradation of seals, reinforcements in compressor stations, valves, new pipelines would be required (Gasunie 2019). For longer distances (e.g., through continents), hydrogen (mainly through ammonia) can be transported as liquid gas, which is a well-known industry world-wide. Short-distance transport within district areas, can be carried out with existing gas infrastructure, while some hydrogen storage may be required.

Improvements in hydrogen use are emerging quickly. General Electric (GE) gas turbines are now running on fuels that contain a 5%-95% hydrogen by volume (GE 2020). Gas turbines could be able to operate completely on hydrogen by 2030 (Simens 2019). The Japanese government has invested in hydrogen fuel infrastructure (Meti 2017) to support hydrogen-based fuel cell vehicles. In the ZEFER project (ZEFER 2020), 180 fuel cell vehicles will be deployed by 2022 in Europe to investigate the business case for hydrogen vehicles. Hyundai is aiming to produce 700,000 fuel-cell based engines by 2030 (Powerlinks 2018). Further improvements of fuel cell technologies are needed to make hydrogen-based transport economically viable. There are also safety concerns associated with flammability (Nilsson et al. 2017), toxicity (Bicer and Dincer 2017; EPA 2001), and storage (Eberle et al. 2009) in the context hydrogen carriers and use in appliances.

6.6.2.5 Using Less Energy and Using It More Efficiently

Demand-side or demand reduction strategies include technology efficiency improvements, other strategies that reduce energy consumption (Creutzig et al. 2018) (such as reducing the use of personal transportation, often called “conservation”), as well as strategies such as load curtailment.

Net zero energy systems will use less energy and use it more efficiently than those of today (*high confidence*). Energy efficiency and energy use reduction strategies are generally identified as being flexible, cost-effective, with a potential for large scale deployment (see Chapters 5, 9, 10 and 11). For this reason, existing studies on net-zero energy systems find that energy efficiency and demand reduction strategies will be important contributors (Creutzig et al. 2018; Davis et al. 2018; DeAngelo, 2021), reducing the need for low-carbon energy or alternative fuel sources.

Characterising efficiency of net-zero energy systems is problematic due to measurement challenges (*high confidence*). Efficiency itself is difficult to define and measure across full economies (Saunderset al., 2021). There is no single definition of energy efficiency, and the definition understandably depends on the context used (Patterson 1996), which ranges from device level efficiency all to way to the efficient use of energy throughout society. Broadly, it is defined as strategies that allow us to enjoy the same level of services or output while using less energy. At the level of the entire economy, measures such as primary or final energy per capita or per GDP are often used as a proxy for energy efficiency, but they reflect not only efficiency but also many other factors such as the structure of the economy, industrial structure, endowed natural resources, and consumer preferences, policies and regulations. In addition, energy efficiency and other demand-side strategies represent such a large set of technologies, strategies, policies, market responses and policies that aggregate measures can be difficult to define (Saunderset al., 2021).

Measurement issues notwithstanding, virtually all studies that address net-zero energy systems assume improved energy intensity than to today (*high confidence*). Future net-zero energy systems will be more efficient but the overall efficiency outcomes and the access to such improvements across different nations is not clear. Energy consumption will increase over time despite energy efficiency improvements due to population growth and development implying we will need more low-carbon energy sources in place with resources and sites that are less efficient (DeAngelo, 2021), DeAngelo (2021), review the outputs for 177 net-zero energy systems scenarios

DeAngelo (2021) review the outputs for 177 scenarios at the point at which they reach net-zero CO_2 emissions, of which 158 reach net-zero emissions in the energy sector specifically. They find that global final energy per capita lies between 21 and 109 GJ/person (median: 57), as compared to global final energy use today (2018) of 55 GJ/person. Across regions, energy use per capita varies more broadly, and many countries use far more energy per capita than today as their incomes increase. Global final energy use per unit of economic output ranges from 0.7 to 2.2 EJ/USD trillion (median: 1.4,), as compared to 5 EJ/USD trillion in 2018. Across all scenarios reviewed that meet net-zero energy systems, the median final energy consumption is 522 EJ (versus 550 EJ if one to assume current levels of energy consumption and a population of 10 billion). However, across all scenarios, final energy consumption is higher than todays' levels. Regionally, DiAngelo et al. (in progress) find that only OECD+EU and Eastern Europe+Russia have lower total final energy than in 2010. Looking at per capita final energy, OECD+EU decreases significantly from 2010 to net-zero year while all other regions increase their energy use.

Net-zero energy systems will be characterised by greater efficiency and more efficient use of energy across all sectors, but with the degree of improvement varying across sectors (*high confidence*). Road transportation efficiency improvements will require a shift from liquid fuels, as the improvements in the internal combustion drivetrains are very limited (Chapters 5 and 10). The gains will instead come from a transition to electrification and hydrogen. Vehicle automation will enable additional efficiency gains by optimising driving cycles for freight travel and personal driving. Ride-hailing services and online shopping with door delivery services will continue to grow with zero carbon vehicles rather than using personal vehicles. “Empty miles” between passengers' drop-offs and picks-up may counteract some of the efficiency gains. Lighter vehicles, shift to public transit, as well as 2- and 3-wheelers will encompass a net zero energy system. Last mile delivery services may rely also on drones, which will likely be less efficient than electrified or hydrogen road vehicles, but more efficient than conventional delivery trucks. Teleworking and automation of work may provide reduction in driving needs. In other sectors, such as air travel and marine transportation will may rely on biofuels.

Buildings will benefit from improved construction materials, increase of multi-family dwellings, early retirement of inefficient buildings, smaller floor areas, and relying on ICT technologies to optimise the efficient use of energy in the building, namely for heating, cooling, LED lighting, and water heating (see Chapter 9). End-uses will use electricity or hydrogen produced with zero carbon sources. The use of electricity for heating and cooking is a less efficient process than using natural gas (i.e., new fuels or energy carriers does not equate with more efficiency). Changes in behavior may contribute with a modest lowering of demand. Developed economies will have buildings with more efficient technologies powered by zero carbon electricity. Developing economies will shift from biomass to electricity and increase in energy consumption as population and wealth increase.

Industry has seen major efficiency improvements in the past, but many processes are now close to their thermodynamic limits (see Chapter 11). Breakthrough processes (such has producing steel with electricity and H2), using recycled materials, using heat more efficiently by improving thermal insulation, using waste heat being for heap pumps, as well using advanced sensors, monitoring, visualisation and communication technologies may provide further efficiency improvements.

6.6.2.6 Greater Reliance on Integrated Energy System Approaches

Energy systems integration refers to the connected planning and operations across a range of energy carriers such as electricity, fuels, and thermal resources. Coordinated planning could be important to lower system costs, increase reliability, minimise environmental impacts, and ensure that lumpy costs of R&D and infrastructure account not just for current needs but also for those of future energy systems. Integration includes not only the physical energy systems themselves but also simultaneous societal objectives (e.g., sustainable development goals), innovation processes (e.g., coordinating R&D to increase the likelihood of beneficial technological spillovers), and other institutional and infrastructural transformations (Sachs et al. 2019). Given system variability and differences in regional resources, there are economic and technical advantages to greater coordination of investments and policies across jurisdictions, sectors, and levels of government (Schmalensee and Stavins 2017). Coordinated planning and operations can improve system economics by sharing resources, increasing the utilisation of capital-intensive assets, enhancing the geographical diversity of resource bases, and smoothing demand. But in integration can require regulatory and market frameworks to facilitate.

Carbon- neutral energy systems will be more interconnected than those of today (*high confidence*). The many possible feedstocks, energy carriers, and interconversion processes imply a greater need for the integration of production, transport, storage, and consumption of different fuels (Davis et al. 2018a). For instance, electrification is expected to play an important role in decarbonising light-duty vehicles (see Section 6.5.4.3), yet the electric power and transport sectors have few direct interactions today. Systems integration and sectoral coupling are increasingly relevant to ensure that net-zero energy systems are reliable, resilient, and affordable (EPRI 2017; O'Malley et al. 2020; Buttler and Spliethoff 2018) Martin et al. 2017). Deep decarbonisation offers new opportunities and challenges for integrating different sectors as well as supply- and demand-side options. For instance, increasing electrification will change diurnal and seasonal load shapes, and end-use flexibilities and constraints could impact the desirability of different supply-side technologies (EPRI 2019b; Brown et al. 2018). The feasibility of net-zero energy system configurations could depend on demonstrating cross-sector benefits like balancing variable renewables in the power sector and on offering the flexibility to produce multiple products. For instance, low-emissions synthetic fuels could help to bridge stationary and mobile applications, since fuel markets have more flexibility than instantaneously balanced electricity markets due to the comparative ease and cost of large-scale, long-term storage of chemical fuels (Davis et al. 2018a).

There are few detailed archetypes of integrated energy systems that provide services with zero- or net-negative CO_2 emissions, so there is considerable uncertainty about integration and interactions across parts of the system. Although alternate configurations, tradeoffs, and pathways are still being identified, common elements include fuels and processes like zero- or negative-CO_2 electricity generation and transmission, hydrogen production and transport, synthetic hydrocarbon production and transport, ammonia production and transport, and carbon management, where linkages across pathways could include the use of electricity to produce hydrogen via electrolysis (Davis et al. 2018; Jenkins et al. 2018b; Van Vuuren et al. 2018; Shih et al. 2018; Moore 2017; Smith et al. 2016).

In light of these uncertainties, there are modeling and analysis needs for cross-disciplinary systems integration research. Linked analytical frameworks can inform system coupling (Gerboni et al. 2017; Santen et al. 2017; Collins et al. 2017; Bistline and de la Chesnaye 2017; Bohringer and Rutherford 2008). For instance, top-down integrated assessment modeling can be complemented by bottom-up, sector-specific models so that cross-sector and global responses can iterate with models that include technological and behavioral detail. Increased supply- and demand-side integration creates a need to understand behaviors of decision-makers in different sectors and to quantify differences for firms and households (see Chapter 5). This poses challenges, given low-levels of experience with emerging technologies, nascent markets, and variation in household preferences and socioeconomic characteristics (McCollum et al. 2018; Muratori et al. 2020). Previous sector coupling studies tend to focus on a few demand sectors (e.g., Brown et al. 2018; Meibom et al. 2010) or, in the case of integrated assessment models, prioritise broad coverage of sectors and geographies over temporal resolution, spatial resolution, and heterogeneity of consumer and firm decisions.

Challenges associated with integrating net-zero energy systems include rapid technological change, the importance of behavioral dimensions in domains with limited experience and data, policy changes and interactions, and path dependence. Technological cost and public acceptance will be influence the degree of integration. Sectoral pathways will likely be adaptive and adjust based on the resolution of uncertainties over time, and the relative competitiveness will evolve as the technological frontier evolves, which is a complex and path-dependent function of deployment, RD&D, and inter-industry spillovers. Supply-side options interact with demand-side measures in increasingly integrated energy systems (Van Vuuren et al. 2018; Sorrell 2015).

6.6.2.7 Use of Carbon Dioxide Removal

Carbon dioxide removal (CDR) technologies will likely be part of net-zero emission energy systems, potentially removing 5-12 Gt-CO_2 yr^{-1} globally (*high confidence*) (Fuss et al. 2018, Figure 6.22). CDR is not intended as a replacement for emissions reduction, but rather as a complementary effort to manage hard-to-decarbonise sectors and offset residual emissions from other low-carbon technologies such as fossil CCS (McLaren et al. 2019; Gaffney et al. 2020) . The amount of CDR necessary to limit warming to 1.5°C or 2°C will depend on the intensity of emissions reductions in the coming decade (Luderer et al. 2018) – less mitigation today will require more CDR in the future. There are some scenarios in which CDR stores less than 5 Gt-CO_2 yr^{-1}, but these scenarios require more than 40% reduction in primary energy compared to today (Van Vuuren et al. 2018; Grubler et al. 2018).

While CDR is likely necessary for net-zero energy systems, the scale and mix of strategies is unclear – nonetheless some combination of BECCS and DAC are likely to be part of net-zero energy systems (*high confidence*). CDR covers a broad set of technologies and strategies (Chapter 7, 12), and two prominent CDR technologies are BECCS, which is used to produce energy carriers, and DAC which is an energy user (Smith et al. 2016). Other options would not interact as directly with energy system operations. In addition to its CDR capability, BECCS has value as an electricity generation technology, providing firm, dispatchable power to support electricity grids with large amounts of variable renewable, and reducing the reliance on other means to manage these grids, including electricity storage

(Mac Dowell et al. 2017). BECCS may also be used to produce liquid fuels or gaseous fuels, including hydrogen (Muratori et al. 2020b). For instance, CO_2 from bio-refineries could be captured at <USD 25/t-CO_2 (Sanchez et al. 2018). Similarly, while CO_2 capture is expensive, its integration with hydrogen via biomass gasification can be achieved at incremental capital cost of 3-35% (Muratori et al. 2020b). As with all uses of bioenergy, linkages to broad sustainability concerns may limit the viable development, as will the presence of high-quality geologic sinks in close proximity (Melara et al. 2020).

DAC offers a modular approach to CDR with less infrastructural coordination (Creutzig et al. 2019b). DAC could be a significant consumer of energy, but captured CO_2 could be reused to produce low-carbon methanol and other fuels (Realmonte et al. 2019; Hoppe et al. 2018;Zhang et al. 2019a). DAC might also offer an alternative for use of excess electricity produced by variable renewables (Wohland et al. 2018) though there are uncertainties about the economic performance of this integrated approach.

6.6.3 The Institutional and Societal Characteristics of Net-zero Energy Systems

The transition to net-zero energy systems is not just technological; it requires shifts in institutions, organisations, and society more generally. As such, it involves changes in the institutions, alongside changes in supply, technology, or markets (Andrews-Speed 2016). There are at least three ways in which institutions are instrumental for net-zero energy systems, complemented by and interacting with the behaviors of actors in these systems (Figure 6.24).

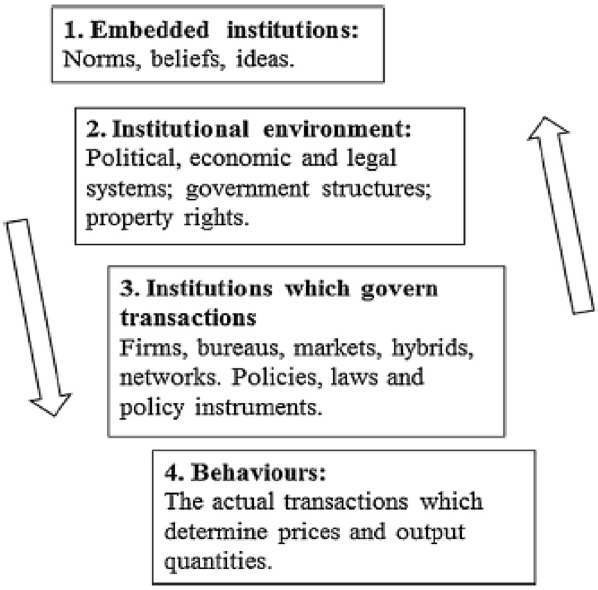


Figure 6.24 The three levels of institutions (1-3) which collectively govern actor behaviors (4).
Source: Andrews-Speed 2016

One level of institutional interactions reflects embedded institutions, norms, beliefs, and ideas that would need to be different than today to support net-zero energy systems. This applies, for example, to the objectives of modern economies and the potentially contradictory dynamics embedded in the concept of “green growth” (Stegemann and Ossewaarde 2018; Stoknes and Rockström 2018). Second, the institutional environment – the political or legal systems that govern exchanges or protect property rights – would need to be different. Here challenges might relate to changing regulations or subsidies that continue to favor carbon-intensive systems over the technologies of a net-zero energy system (Sovacool 2017). More generally, net-zero energy systems will need new regulatory frameworks to, for example, manage a more interconnected grid or manage underground storage of CO_2. A third level of institutions govern specific transactions, such as firms or networks that supply energy fuels or services. Current actors such as these are typically resistant to disruptions, even if such disruptions may broadly benefit society (Kungl 2015). Examples include China, where some state planners seek to curtail renewable energy (Mori 2018), or Germany, where research suggest DSOs are hostile to renewable electricity (Schmid et al. 2017).

To give an example, it has been asserted that the U.S. energy system has two broad institutional wings, one based upon lightly-regulated delivery of liquid fuels, and another based upon closely- regulated delivery of electricity (Dworkin et al. 2013). Reforming this two-pronged system for decarbonisation would require four types of institutional change: (1) institutional changes to the control systems that coordinate generation and transmission through a pyramidal architecture for the operational control, dispatch, and delivery of power with a primary emphasis on reliability; (2) institutional changes to the financing of central -station power plants through long-term bonds, as valued by Wall Street ratings analysts; (3) institutional changes to the structure of investor-owned utilities that attract private investors who expected decades of technological stability to yield long-term, low-risk revenues; and (4) institutional changes to regulations to restructure and limit excessive returns and easy entry of new retail competitors, and which that recognised both local and national concerns through both state and federal regulatory agencies. Internationally and across different parts of the energy system, institutional challenges such as these could become even more stark and complex (Van de Graaf 2013).

6.6.4 Regional Circumstances and Net-zero Energy Systems

Countries have flexibility to pursue options that make the most sense for their national circumstances (Figure 6.25). They may emphasise supply transformation over demand reduction; deploy different resources; engage at different levels in international energy trade; support different energy industries; focus on different energy carriers (e.g., electricity, hydrogen); focus more on distributed or integrated systems, among others. How can countries navigate this space in a meaningful way to identify the long-term net-zero energy systems that are appropriate for their national circumstances? A number of factors might influence the answer.

Future Technology. Perhaps the largest and most critical factor is the nature of future technology. Technological transitions have largely been driven by the economics of different technology options. Recent trends in the use of PV cells and in electric cars, for example, have been driven by the increasing economic competitiveness of these technologies (Section 6.3). At the same time, future technology cannot be fully predicted, so it provides only a partial guide to decision makers today assessing their future options.

Indigenous Energy Resources. Countries might anticipate emphasising approaches that take advantage of indigenous resources such as solar power, wind, hydroelectric resources, agricultural land, CO_2 storage capability, or fossil resources to be use used with CCUS. Countries with less abundant resources may put greater emphasis on demand reductions and regional integration. Countries with resource bases that are easily tradeable, for example, low-carbon electricity or potentially bioenergy, may choose to trade those resources rather than using them domestically. For example, regional electricity markets could allow countries endowed with expansive renewable electricity resources to produce beyond their own domestic needs if they can find other countries to purchase fuels generated from these resources.

Regional Climate. Climate will influence the heating and cooling demands, and these constitute a large portion building energy demands. Historically, cooling has been served by electricity and heating has most commonly been served by gaseous, liquid, and solid fuels. In net-zero systems, however, heating may be increasingly served by electricity through the use of heat pumps (Section 6.6.4), limiting the distinction between fuel types emerging from differences in climate. At the same time, heating and cooling are seasonal, both influencing which energy sources may serve these loads and the degree of seasonal storage that would need to be included in any energy system.

Current Energy System Configuration. Countries will tend to build on their current system configurations. Countries with less developed or growing energy systems will have more flexibility to create the systems that best match their long-term goals, but there may be substantial challenges is moving directly to the most advanced technology options. Future sectoral energy demands and the potential for demand-side transformation are partially determined by existing infrastructure (e.g. building stocks, transport infrastructure).

Regional Integration. Regional integration allows countries to bridge gaps using external linkages, including regional electricity integration, trade in biomass resources. Countries with greater integration can rely more heavily on non-indigenous resources and will therefore be less disposed to have their net-zero energy systems dependent on those resources. (Box 6.8)

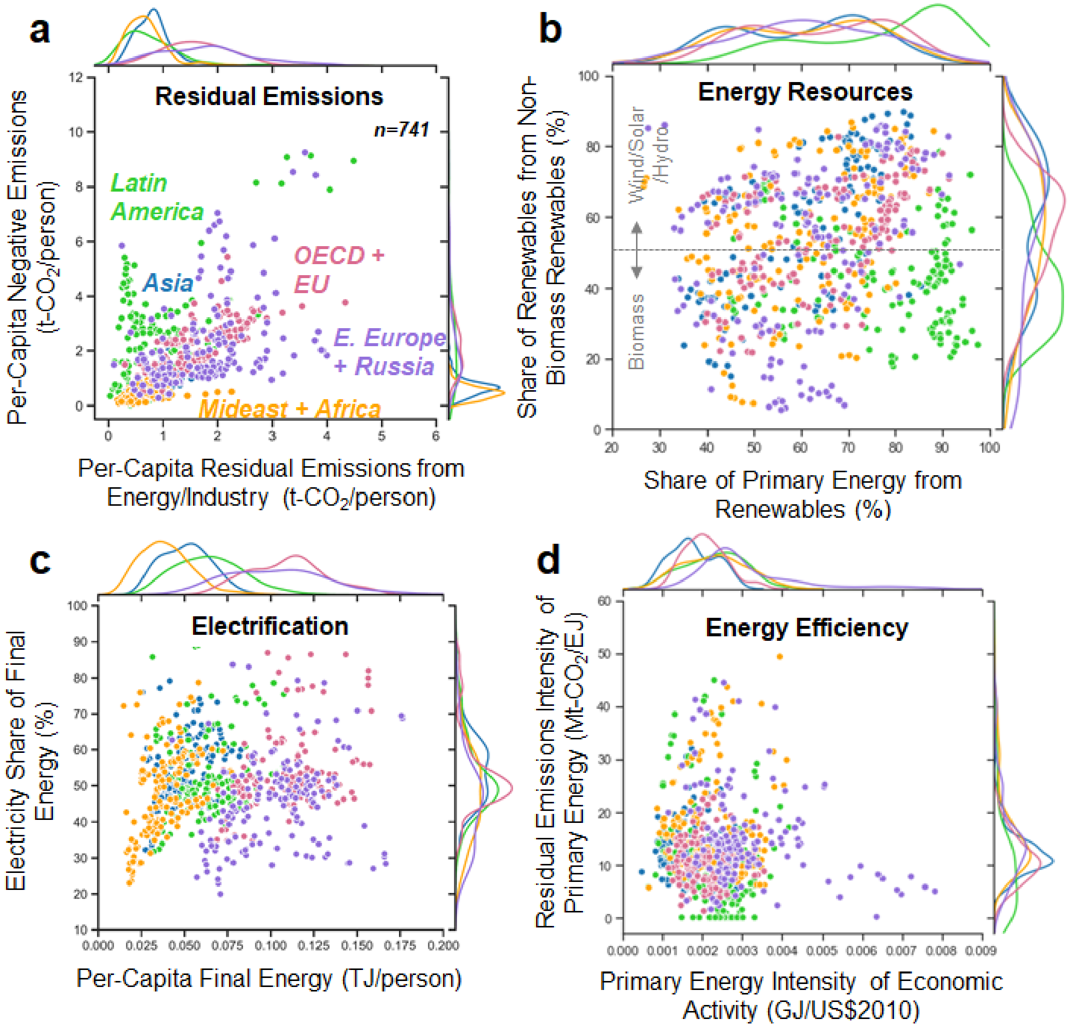


Figure 6.25 Characteristics of regional energy systems and emissions when energy and industrial CO_2 emissions reach net-zero. Scenarios reaching net-zero emissions globally show regional differences in residual emissions and carbon removal (a), energy resources (b), electrification (c), and energy efficiency (d). Probability density distributions shown along each axis for each region (Asia = blue, Latin America = green, Middle East + Africa = orange, OECD + EU countries = pink, and Eastern Europe + Russia = purple).

Societal Preferences. Citizens in every country have preferences for some technological options or mitigation approaches over others. Research indicates that the public generally prefers futures based largely on renewable energy (Xexaki & Trutnevyte, submitted). Preferences for non-renewable energy differs across regions and groups (Xexaki & Trutnevyte, submitted). For example, people in the U.S. and Canada are willing to pay more for electricity produced by renewables compared to the current energy mix (Sergi et al. 2018). People in the Europe, including the U.K., Germany, the Netherlands, and Switzerland, prefer renewable energy and personal efficiency and energy saving to nuclear, fossil fuels and CCS (Demski et al. 2017; Jones et al. 2012; (Scheer et al. 2013) Volken et al. 2018, Bessette and Arvai 2018(Steg 2018). People with higher education levels, higher incomes, females, and liberals prefer renewables to fossil fuels and nuclear (Van Rijnsoever et al. 2015; Bertsch et al. 2016; Blumer et al. 2018; Jobin et al. 2019) and the willingness to pay for renewable electricity differs by source (Ma et al. 2015; Sundt and Rehdanz 2015).

Technological Leadership, Economic Opportunities, and Growth. Countries might emphasise technologies in which they intend to have technological leadership and a competitive advantage. These could emerge over time or be based on current areas of opportunity or leadership. Industrial policy can more generally influence climate policy as technological choices can benefit or hamper incumbents or new market actors.

Energy Security. Use of indigenous resources tends to reduce energy security concerns from energy imports. Countries emphasising import security will tend to emphasise indigenous strategies. Renewables, particularly bioenergy and hydropower, can be subject to import climate risks, influencing energy security even from indigenous resources, calling for a broader energy mix or greater regional integration.

Other Factors. Countries will take into account a wide range of additional factors in building toward long-term net-zero energy systems. Other factors might include population density, which would influence the nature of buildings, energy use, and transportation. Sustainable development goals in general tend to lean toward certain types of energy systems.

Box 6.8 Regional Integration of Energy Systems

Energy systems are linked across countries in many different ways. Countries transport crude oil across the ocean in supertankers. Pipelines carry oil and natural gas across country boundaries. Electric power lines cross country boundaries. And countries trade industrial commodities that carry embodied energy or that are essential inputs to mitigation technologies. Future systems will generate electricity using different mixes of technologies, produce and transport different carriers (e.g., hydrogen or biofuels), and use far less fossil fuels, among other major changes. How might regional integration in net-zero energy systems be different than it is today?

Electricity System Integration. Given the significant variations in renewable resources and the timing of these resources – notably wind and solar PV – across different regions, regional electricity grids could reduce the costs of net zero energy systems. There may be significant benefits in integrating regional electricity transmission infrastructure to enable cost effective deployment of renewable generation. For example, fully coordinated deployment and management of renewable sources in Europe by 2030, would save 160 GW of renewable capacity while producing the same amount of renewable energy and save more than €150bn in investment (Newbery et al. 2013). Furthermore, interconnection can significantly reduce the local energy balancing cost and investment in peaking plants needed to meet security of supply requirements, and it can increase system resilience, especially in case of extreme events such as heat waves or cold spells (Dmitrii et al. 2016). Comparable examples can be found in Asia and around the world. Climatic dipoles present both regionally and on continental scales could also help support diversification of renewable energy sources and mitigation of risk due to complementary weather and climatic phenomena. Electricity from solar generation produced in Middle East (with higher capacity factors) could be used in Europe even after sunset. Further integration between Europe and MENA could also have significant mutual economic benefit and support increasing decarbonisation, potentially significantly contributing to a fully decarbonised system by 2030 (Dawkins 2019; Bogdanov et al. 2016). At the same time, a broad range of geopolitical and socioeconomic challenges will need to be overcome to support this level of international co-operation, as well as the techno-economic challenges associated with large-scale network expansion.

Hydrogen Integration. If hydrogen plays a significant role in future net-zero energy systems, there may be needs to transport hydrogen across long distances. In net-zero systems with substantial wind and solar power generation, hydrogen can be generated through electrolysis and then shipped to other locations. For example, there is significant interest in producing hydrogen in the North Sea by offshore wind generation and also in the Middle East by solar generation. Hence, there is growing interest in infrastructure for transport of hydrogen over both short and long distances.

Trade in Biomass. Large-scale bioenergy requirements in net-zero energy systems are likely to trigger major global trade of biomass, potentially on a scale similar to fossil fuel trade today. Global bioenergy trade volumes presently exceed 1 EJ, of which 60% is directly traded for energy purposes (Proskurina et al. 2019b). Currently established trade mechanisms include wood pellet transport (~12000 ktons), ethanol (~4000 ktons) and biodiesel (~7000 ktons) (Proskurina et al. 2019a). Under a net-zero context, trade of bioenergy is projected to be greater than current trade of coal or natural gas, but less than that of petroleum. Most models agree that Latin America and Africa are projected to be the main exporting regions, with EU, the USA and East Asia being key importers (Rentizelas et al. 2019; Alsaleh and Abdul-Rahim 2018). Thus, net bioenergy exports may be as high as 10% of the GDP for some Latin American countries while creating considerable import reliance in the EU (Mahlknecht et al. 2020; Daioglou et al. 2020b). Note that an accelerated timeline towards net-zero emissions does not necessarily imply greater bioenergy trade as such scenarios are also associated with reductions in final energy demand.

6.7 Energy System Transitions in the Near- and Medium-Term

6.7.1 Transition Pathways to low carbon energy systems

6.7.1.1 Pathways for CO_2 emissions from energy system

Without additional efforts to reduce emissions, energy system emissions are very likely to continue to increase in the coming decade and beyond (*high confidence*). Scenarios assuming no additional climate policies beyond those in place today provide a useful benchmark for comparison against mitigation scenarios (Figure 6.26). Global CO_2 emissions fossil fuel combustion increase in these “baseline” scenarios but span a broad range, reflecting underlying differences in the potential development of future energy systems (Bauer et al. 2017a; Riahi et al. 2017; Wei et al. 2018).). The highest baseline emissions from the energy sector, are about four times larger than current emissions; the lower baseline emissions are modestly below today’s levels. All of these scenarios, assume meaningful improvements in technology. While the realism of these different possible baseline scenarios can be debated – particularly in an environment today of increasing climate action – the fact that they are general increasing strongly supports the conclusion that the energy sector will not be decarbonised without explicit policy actions to reduce emissions. Although baseline emissions increase in most of the regions, they diverge significantly across regions. Asia and the Middle East and Africa are responsible for the majority of increased emissions across scenarios (Figure 6.27).

Limiting warming to 1.5°C will require that energy sector emissions decline at about 2.2–3.3% annually through 2050 to limit warming to 1.5°C; they will need to decline at about 1.3–2.2%a annually to limit warming to 2.0°C (*medium confidence*) (Figure 6.26). While the range of emissions pathways is relatively narrow, there are significant differences in energy system and socioeconomic transformations (Box 6.9). All other things being equal, lower energy demand growth will ease the transition, and continued dependence on fossil fuels and delayed efforts to reduce emissions will pose substantial challenges, potentially requiring substantial net negative emissions technologies in the second half of the century to offset emissions in the first half (Bauer et al. 2017a; Kriegler et al. 2017).

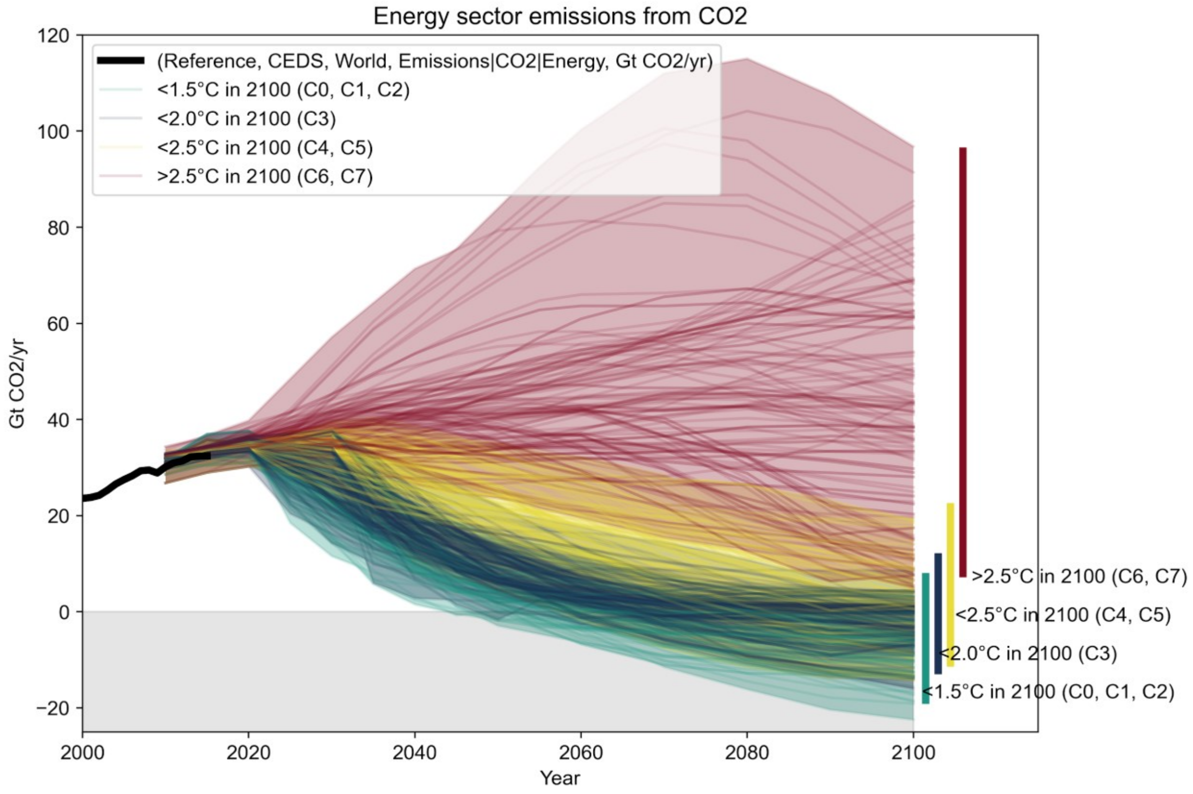


Figure 6.26 Global CO_2 emissions from energy (IPCC Scenario Database)

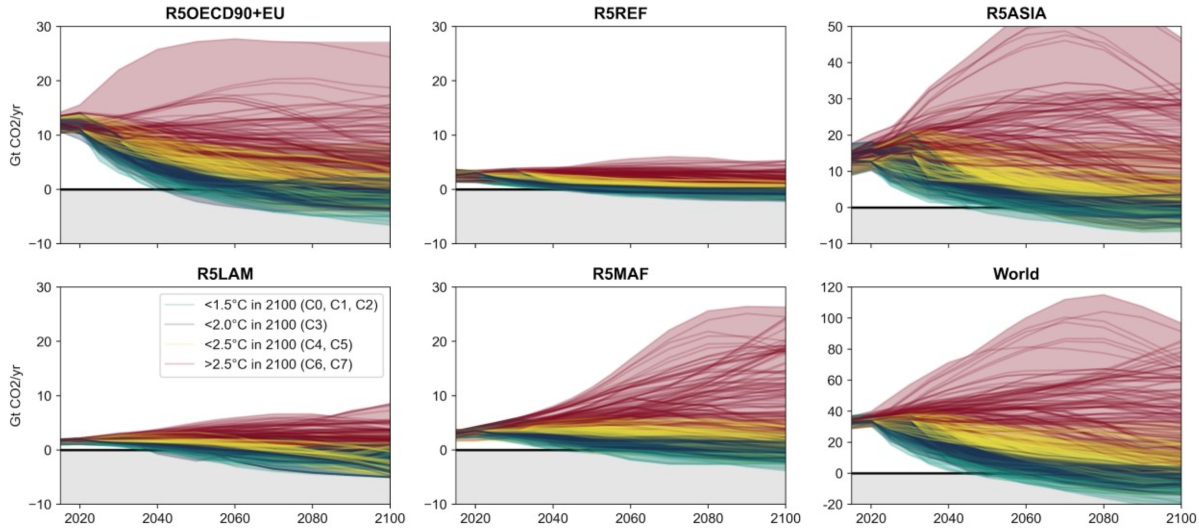


Figure 6.27 Regional CO_2 emissions from energy (IPCC Scenario Database)

6.7.1.2 The timing of net-zero energy systems

The global energy systems will need to reach net-zero CO_2 emissions around 2050-2065 to limit temperature change to 1.5°C; it will need to reach net-zero around 2065-2095 to limit warming to 2.0°C (*medium confidence*) (Figure 6.28). Achieving net-zero CO_2 emissions is requisite for stabilising warming because cumulative emissions of CO_2 largely determine the degree of warming. Overall GHG emissions reach net zero after the energy system becomes reaches net-zero, because substantial non-CO_2 emissions are expected to continue indefinitely. The year of net-zero energy system CO_2 emission moves earlier as the climate target becomes stringent. The availability of net zero or negative emissions technologies and the stringency of climate policy, among other factors, determine the timing of net zero emissions.

The power sector is anticipated to reach net-zero emissions before other sectors (*medium confidence*) (Figure 6.28). Research indicates that it will be easier to reach net-zero in the power sector than in other sectors, because of the number of low-emissions, zero-emissions, and negative-emission options relative to other sectors (Rogelj et al. 2018a, Rogelj et al. 2015b; Clark and Herzog 2014; IPCC 2018; Luderer et al. 2018). Power sector net-CO_2 emissions reach zero around 2050 in 1.5°C scenarios and after 2050 (2045-2070) in 2°C scenarios (Figure 6.28). The full energy sector reaches net-zero around 20 years after the power sector in almost all scenarios for 1.5°C, whereas energy and industrial process emissions reach net-zero this century in only two-thirds of 2°C scenarios. The energy system includes sectors that are relatively easy to electrify and are expected to reduce emissions early, such as residential heating, as well as sectors that are difficult to electrify and hard to decarbonise at an affordable cost, such as the long-distance transportation, industrial processes, and high-temperature heat. These, harder-to-decarbonise sectors are expected to be decarbonised last, after the power sector (Figure 6.28).

The timing of net-zero energy systems will vary by region depending on the structure of regional energy systems and domestic circumstances. Regions with a relatively large potential for CDR, abundant domestic low-carbon resources, and modest drivers of increased energy system growth can generally reach net zero emissions earlier. Many scenarios indicate that Latin America will reach net-zero energy system emissions more quickly than other regions due to the substantial bioenergy potential, but this depends critically on the feasibility of utilising that potential and the nature of future bioenergy trade (Figure 6.27).

Delays in climate action will move up the feasible times at which energy systems can reach net-zero CO_2 emissions and require a rapid transformation of energy systems (*medium confidence*). A two-decade delay in the peak in global energy system CO_2 emissions will bring forward the feasible timing of net-zero energy system emissions by about 15 years to limit warming to 2 °C. The timing of net-zero energy system CO_2 emissions has an inverse relationship with peak emissions. For a given CO_2 budget, higher near-term emissions require a steeper decline in future CO_2 emissions. Higher CO_2 levels of about 45 $GtCO_2$ in 2030 lead to earlier net zero CO_2 emissions around 2065, and lower CO_2 levels of about 25 $GtCO_2$ in 2030 correspond to later net zero CO_2 emissions around 2080 (Rogelj et al. 2015b).

We lack sufficient understanding to pin down precise dates at which energy systems in individual countries, regions, or sectors need to reach net-zero to limit warming to any particular level (*high confidence*). Current understanding can, however, can provide rough ranges. Net-zero timing is based on a number of factors that cannot be known today or are bound up in the approaches that countries or regions might take to reduce emissions. The future of key technologies, such as energy storage or hydrogen, is not well understood. The discount rate used to assess strategies affects the timing of mitigation and therefore the timing of net-zero energy system emission (Mercure et al. 2018; Bednar et al. 2019). Higher discount rates tend to defer climate investments, and vice versa. The use of CDR in the latter half of the century could reduce the pressure on mitigation today, but is subject to a wide range of feasibility concerns (Obersteiner et al. 2018). Lower discount rates lead to lower future carbon prices and less overshoot of the carbon budget with less negative emissions, and thus the year of net zero carbon emissions are delayed (Emmerling et al. 2019). Definitions and methodological choices also matter, such as the use of LULUCF data and accounting of negative emissions resulting from BECCS. The former especially affects the timing of net zero emissions in countries with large sinks or sources.

The latter has implications for biomass importers and exporters: when allocating negative emissions from BECCS to the biomass-producer rather than the country applying CCS, biomass-exporting countries would see an earlier phase-out.

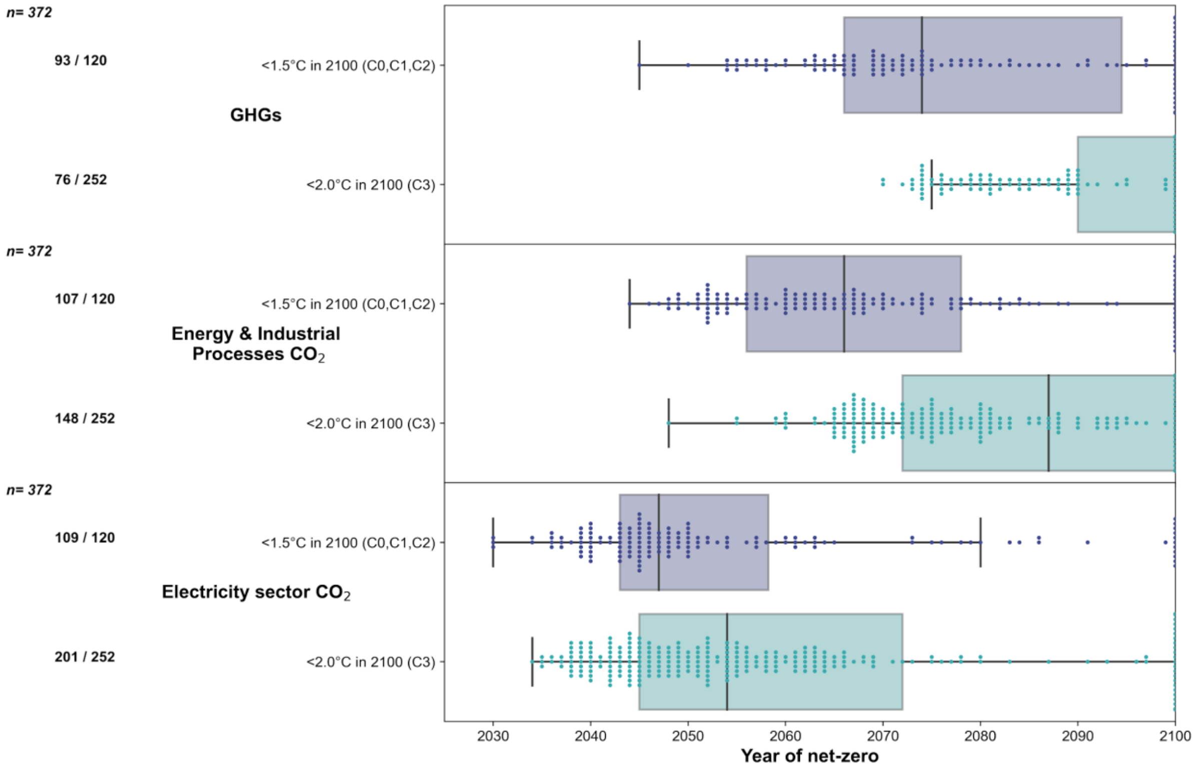


Figure 6.28 The timing of net-zero emissions. Fraction indicates the number of scenarios reaching net-zero by 2100 out of the total sample size.

6.7.1.3 Energy transition strategies

Limiting temperature change requires a fundamental transformation of energy systems, and there are multiple technological routes to achieve the targets (*high confidence*). The power sector presents the most viable near-term opportunity to reduce emissions, due to the availability of renewable energy sources such as wind and solar power, nuclear power, and CCS technology. At the same time, energy efficiency improvements and energy conservation can reduce energy demands, and the use of electricity can be increased in applications such as heating, cooking, and vehicles, reducing fossil fuel consumption. In sectors where electrification is difficult, such as long-distance transport (freight, aviation and shipping) and energy intensive industries, alternative fuels or energy carriers, such as biofuels and hydrogen, may be needed. CDR options, such as BECCS and DAC, could be used to offset any remaining fossil fuel CO_2 and GHG emissions. (Section 6.6).

A rapid shift away from fossil fuels is crucial to reduce energy sector CO_2 emissions (*high confidence*). Mitigation scenarios deploy a variety of different energy technologies for mitigation, depending on technology assumptions, scenarios, national circumstances, and national priorities (Krey et al. 2019). Renewable energy, including solar, wind hydropower, bioenergy and geothermal, will have an important role in providing low-carbon energy (Gielen et al. 2019). Fossil fuels with CCS or nuclear may also play important roles (Riahi et al. 2017; Bauer et al. 2017b). The share of low-carbon technologies in energy supply needs to increase, but the configuration of these technologies depends on the regional context and future technological progress. Limiting warming to 1.5°C or 2°C involves a significant reduction in fossil fuel consumption, especially the consumption of coal (Section 6.7.4). Alternatively, non-fossil low-carbon energy sources, renewables, nuclear power, and fossil or bioenergy with CCS need to grow. Bioenergy may be used because it is a versatile substitute for fossil fuels where electrification is not possible. Luderer et al. 2014 find rates of growth of 1–5% per year in bioenergy production through 2050. Hydrogen can also be an attractive option, but the carbon footprint of hydrogen, depends on the primary energy sources and the process used for its production (See Box 6.7). Scenarios generally find that hydrogen consumption will grow more gradually, becoming most valuable after the energy system has become predominantly low-carbon with a large share of low carbon energy sources (Figure 6.29).

To limit warming to 1.5°C (2°C), the share of low-carbon technologies in primary energy supply will need to grow more than five times (more than quadruple) from current levels by 2050 (*medium confidence*). The share of low-carbon technologies in global energy supply today is below 20% (Section 6.3, Chapter 3). Scenarios find that low-carbon technologies reach around 60% (50–70%) of the energy by 2050 for 2°C target, and about 70% (60% to 80%) in 1.5°C scenarios (Figure 6.29).

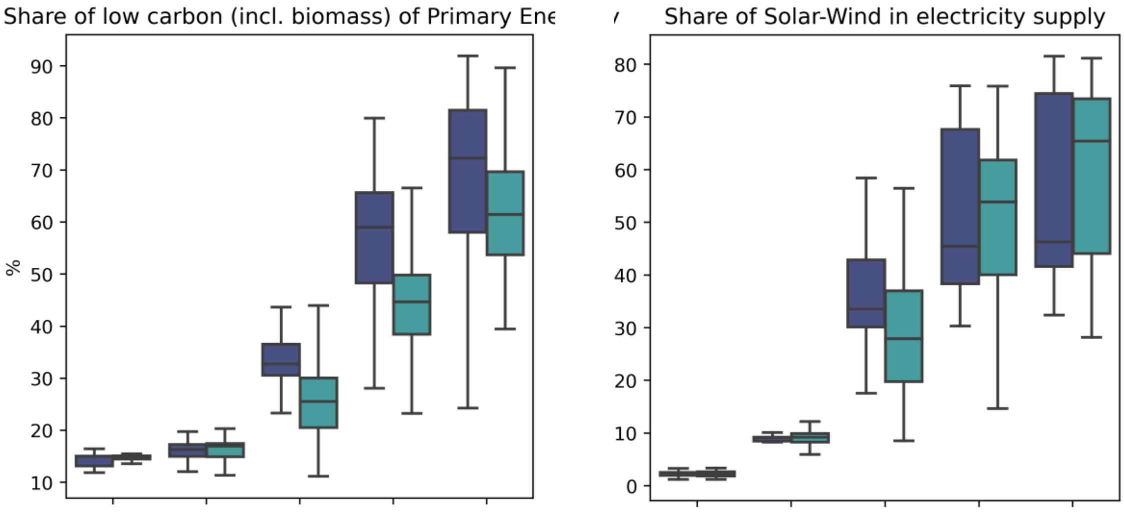
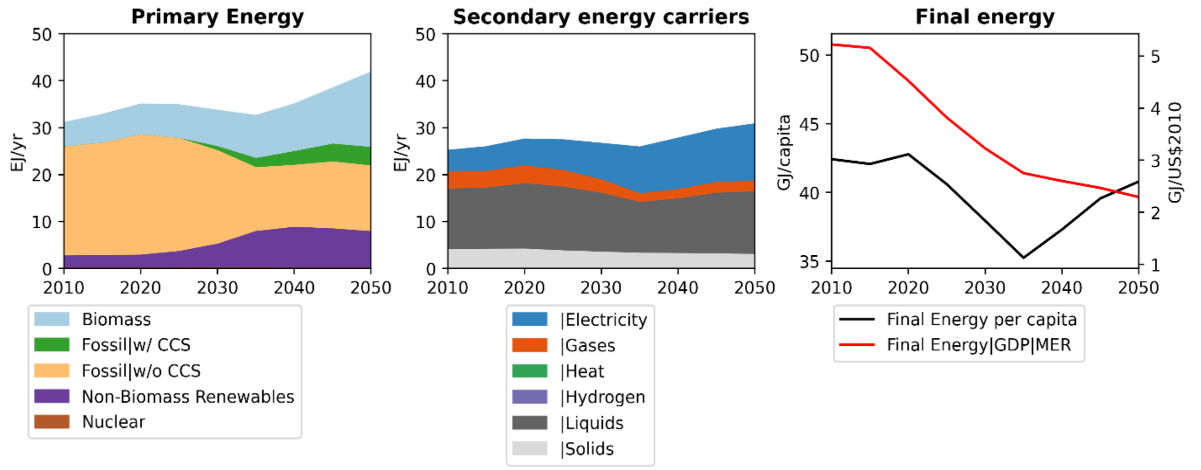


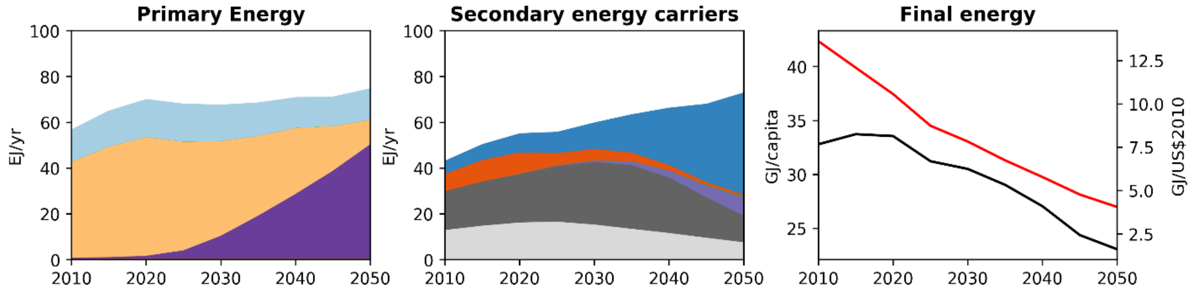
Figure 6.29 Share of low carbon energy of Primary Energy (left) and share of wind and solar in primary energy (right) (Source: IPCC Database)

Box 6.9 Illustrative Energy System Transitions

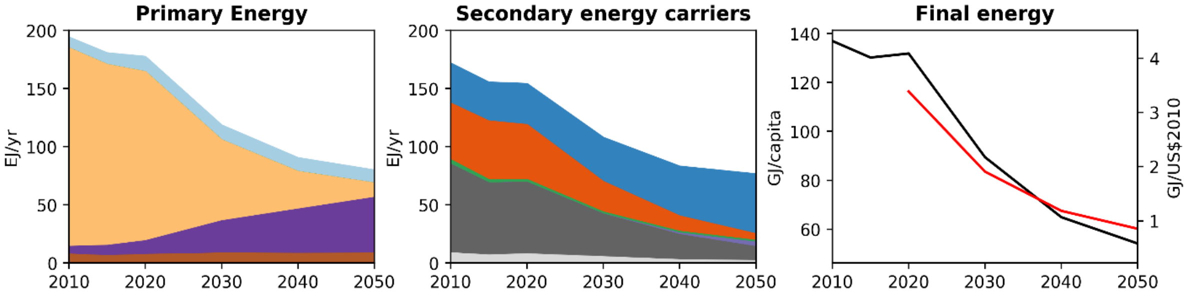
There are multiple possible strategies to transform the energy system to reach net-zero CO_2 emissions and to limit warming to 1.5°C and 2°C. All pathways rely on the strategies for net-zero CO_2 energy systems highlighted in Section 6.6.2, but they vary in the emphasis that they put on different aspects of these strategies and the pace at which they approach net-zero emissions. The pathway that any country or region might follow will depend on a wide variety of factors (Section 6.6.4), including, for example, resource endowments, trade and integration with other countries and regions, carbon sequestration potential, public acceptability of various technologies, climate, the nature of domestic industries, the degree of urbanisation, and the relationship with other societal priorities such as energy access, energy security, air pollution, and economic competitiveness. The illustrative pathways presented in this box demonstrate four distinct strategies for energy system transformations, aligned with global strategies that would contribute to limiting warming to 1.5°C – and they represent very different visions of net-zero energy systems. Yet all of these pathways share the common characteristic of a dramatic transformation over the coming decades.



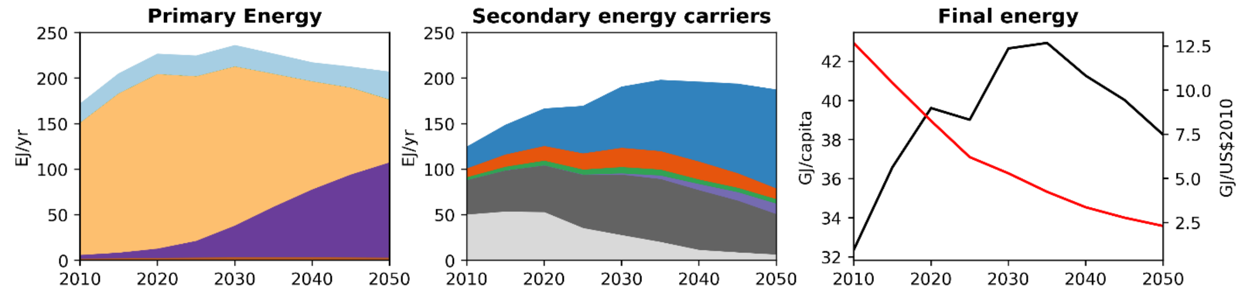
Box 6.9, Figure 1 Illustrative Pathway 1.5-Sup: Latin America & Caribbean in a 1.5°C scenario (net-zero economy, 2038, net zero energy system 2056). Supply side focus with growing dependency on carbon sequestration and AFOLU, thus achieves net-zero very early.



Box 6.9, Figure 2 Illustrative Pathway 1.5-Renewables: Africa & Middle East in a 1.5°C scenario (net-zero economy, 2060, net zero energy system 2057). Rapid expansion of non-biomass renewables, high electrification supported by hydrogen, and a fossil fuel phaseout.



Box 6.9, Figure 3 Illustrative Pathway 1.5-Low Demand: OECD+EU in a 1.5°C scenario (net-zero economy, 2075, net zero energy system 2046). Massive reduction of energy demand, high electrification and FF phaseout.



Box 6.9, Figure 4 Illustrative Pathway 1.5-Shifting Pathways: Asia in a 1.5°C scenario (net-zero economy, 2074, net zero energy system 2094). Renewables, high electrification, FF phaseout and low AFOLU emissions. Reaches net-zero relatively late.

Box 6.9, Table 1. Summary of selected Illustrative Pathways energy system characteristics in 2050 for the chosen regions.

		Energy sector CO_2 Reduction rate2020-2050 %	Energy intensity		Variable renewable capacity		Low carbon capacity additions		Negative Emissions BECCS, AFOLU, Total		GDP per capita		Year net-zero emissions	
		Gt CO_2 yr^{-1}	MJ / USD2010		EJ yr^{-1} (%)		GW yr^{-1}		Gt CO_2 yr^{-1}		MER USD2010/person		Full economy	Electricity
	Region	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050		
1.5-Sup	Latin Am. & Carib.	2.5	4.5	2.3	0.2 (4)	5 (43)	12	42	0, 0.2, 0.2	0.4, 1.5, 1.9	9460	17782	2038	2039
1.5-Ren Africa	Africa	3	10.6	4.1	0.3 (4)	39 (87)	15	440	0, 0.1, 0	0.3, 0, 0.3	3176	5689	2060	2039
1.5-LD OECD	OECD	3.1	3.4	0.9	4 (13)	37 (72)	52	188	0, 0.1, 0.1	0, 0.6, 0.6	38904	63327	2056	2046
1.5-SP Asia	Asia	2.5	8.3	2.3	2.6 (6)	83 (77)	123	684	0, 0.1, 0.1	0, 0.4, 0.4	4793	16555	2074	2094

Decarbonisation of the power sector along with increasing use of electricity is an essential near-term strategy for limiting warming (*high confidence*). Low-carbon electricity generation technologies currently produce less than 40% of the global electricity, but will need to produce almost 100% by 2050 – that is, be fully decarbonised – to limit warming to for either 2°C or 1.5°C (*medium confidence*). A number of studies highlight the importance of power sector in reducing CO_2 emissions from the energy system as a whole (Clark and Herzog 2014; Krey et al. 2014; Williams et al. 2012; Luderer et al. 2018; Zhao et al. 2018; Tang et al. 2018). Low-carbon electricity then facilitates the use of electricity to reduce CO_2 emission than in other sectors of the energy system. Global electricity generation was 26,600 TWh 2018, and associated emissions were about 13 Gt, or 38% of total CO_2 emissions from global energy systems (Section 6.3). Electricity demand roughly doubles by 2050, and quadruples to quintuples by 2100 in both mitigation scenarios and baseline scenarios (Bauer et al. 2017a; Luderer et al. 2017; IEA 2019a).

Electricity plays a key role in decarbonising energy systems (*high confidence*). The percentage of electricity in final energy needs to be increased to over 40% by 2050 to limit warming to 1.5-2°C (*medium confidence*). The current electrification rate globally is about 20%. Accelerated electrification with a combination of full-scale decarbonisation in power supply is one of the core strategies to decarbonise energy system (Waisman et al. 2019; IEA 2019a; Sugiyama 2012; Zou et al. 2015; Rockström et al. 2017; Luderer et al. 2017). Studies find a substantially increased electricity in 2°C and 1.5°C pathways (Riahi et al. 2017; Bauer et al. 2017b; Clarke et al. 2014; Sugiyama 2012; Krey et al. 2014). This includes aggressive electrification of energy end uses, such as widespread use of electric vehicles (EVs), and electric heat pumps for water heating and air conditioning.

Depending on resource endowments and regionally specific circumstances, electrification can be direct or indirect. Direct electrification makes efficient use of domestic low-carbon electricity by transforming end-use technologies (battery-electric vehicles, heat pumps, electric boilers and furnaces). Indirect electrification via electricity-based hydrogen and synthetic fuels (efuels or power fuels) is less efficient but allows for importing low-carbon fuels from countries with abundant low carbon electricity resources (Fasihi and Breyer 2020; Fasihi et al. 2016; Lehtveer et al. 2019). Indirect electrification pathways shift transformation requirements from the demand to the supply side compared to direct electrification.

The percentage of electricity produced globally from variable renewable energy, primarily wind and solar power, is likely to grow to around 30-40% (20-30%) in 2030 to limit warming to 1.5°C (2°C) and reach almost 40-70% in 2050 to limit warming to 1.5°C or 2°C (Figure 6.30). Some authors have argued that wind and solar could produce close to 100% of electricity for individual regions or countries (Hansen et al. 2019), but a range of issues surrounding incorporation of intermittent renewable generation remain unresolved at such high levels of penetration (Section 6.6, Box 6.6). Currently renewables, including solar PV, hydropower, wind and geothermal, supply almost 25% of global electricity output (Section 6.3). The contribution of wind and solar PV in mitigation scenarios varies widely depending on assumptions. Given the strong growth and large resource potential of wind and photovoltaic, VRE could supply more than 60% of electricity over the period of 2050-2100 (Pietzcker et al. 2016; Creutzig et al. 2017). Other studies suggest that more than 30% to 80% of electricity could be supplied by non-biomass renewables in 2050 for the 1.5°C scenarios Rogelj et al. 2018b), while some national and regional scenarios from energy system models explore 100% variable renewable contributions (Hansen et al. 2019; Brown et al. 2018; Breyer et al. 2020).

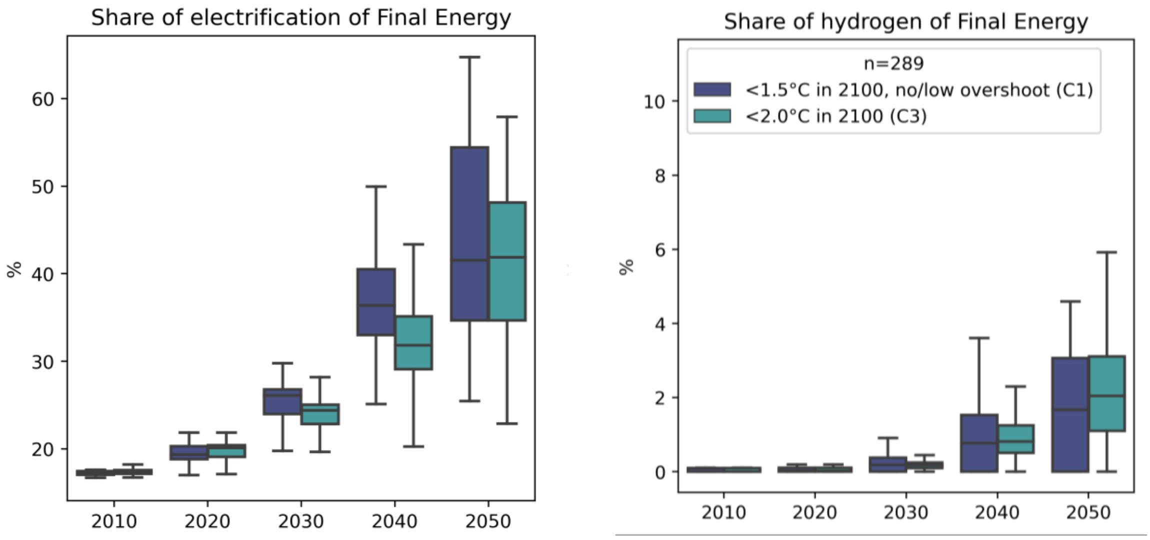


Figure 6.30 Share of electricity in final energy (left) and share of hydrogen in final energy (right)
(Source: IPCC database)

Energy demand and economic development are closely related. Improving energy efficiency is critical to reducing energy demand without undermining economic welfare (*high confidence*). Energy service demand is expected to continue to increase, but there is great uncertainty about how much it will increase (Riahi et al. 2017; Bauer et al. 2017b; Yu et al. 2018) Given the need to produce low-carbon energy, the scale of energy demand is a critical detei rminant of the challenge of mitigation. Higher energy demand increases the challenge due to limited low-energy supply options, whereas lower energy demand increases the feasibility of low-carbon energy supply systems.

Improving energy efficiency, electrifying energy services, and developing alternative technologies in hard to decarbonise sectors are key low-carbon strategies (*high confidence*). Following the power sector, significant decarbonisation is expected in the residential sector, but the industrial and transportation sectors will be decarbonised more slowly and will still involve significant fuel combustion in 2050. Every sector has a range of individual options (see sectoral chapters for more details). In the buildings sector, electrification and energy efficiency improvements are the primary means for decarbonisation (IEA 2019a; Leibowicz et al. 2018; Chapter 9). Available low carbon options are much more limited and costly especially in transport and industry mainly because the potential to use electricity is limited or immature. In addition to electrification, emissions from these sectors would need to be reduced by increasing technical efficiency, reducing energy service demand, fuel switching to biofuels, hydrogen, ammonia or synthetic methane. Mitigation options in the future mobility (See Chapter 10) include the deployment of battery electric vehicles (EV) or hydrogen fuel cell vehicles (FCV), increased use of biofuels in liquid energy carriers, and fuel demand reduction through changing behavior such as modal shift to public transportation, using car-sharing services and reducing car weight. EV, FCV and bio-fuels are expected to increase to meet higher transport demand (Bauer et al. 2017). The industrial sector encompasses a wide variety of subsectors and mitigation measures differ at every subsector from energy and material efficiency improvement, fuel switching, electrification, deployment of carbon dioxide capture, utilisation and storage (CCUS) to utilisation of hydrogen.

Lifestyle changes can contribute to reducing energy demand without reducing the level of energy services (*high confidence*). Lifestyle and behavioral change, such as modal shifts towards more mass transit, car sharing, moderate heating and cooling levels at homes and dietary change to low-meat healthy food, will all reduce energy demand (Van Vuuren et al. 2018).

6.7.1.4 Technology options to offset residual emissions

CDR technologies could be used to offset emissions from sectors that are difficult to decarbonise. CDR is likely to be important in limiting warming, but there is substantial uncertainty about the amount of CDR that might ultimately be deployed for this purpose. In many scenarios, energy sector CDR is deployed to such an extent that energy sector CO_2 emissions become negative in the second half of the century (Clarke et al. 2014). Several studies suggest that CDR is no longer a choice but rather a necessary requirement for the 1.5 °C goal (Luderer et al. 2018; Rogelj et al. 2015a; Van Vuuren et al. 2018; Detz et al. 2018; Strefler et al. 2018). The use of CDR varies across scenarios and is tightly linked to future energy demands. Lower energy demands will put less pressure on the need for CDR. For example, Rogelj et al. 2018a found that for 1.5 °C scenarios, lower final energy demand is associated with the lowest BECCS deployment over the twenty-first century 150–700 $GtCO_2$, compared to 950–1,200 $GtCO_2$ in larger energy demand scenarios.

Many CDR options would directly interact with the energy sector, whereas other would not directly interact, but would, nonetheless have important implications for energy sector transitions by reducing the emissions burden on the energy sector. Bioenergy with carbon capture and storage (BECCS) is an energy supply technology and would therefore be fully integrated into the energy system (see Section 6.4). DAC would use large amounts of energy, but would not be used to supply energy. A broader range of CDR options would not be associated with the energy sector directly, but their use could alter the trajectory and timing of energy sector transitions. This includes afforestation and reforestation, biochar, soil carbon sequestration, enhanced weathering on land and in oceans, and ocean fertilisation (Haszeldine et al. 2018; Minx and Lamb 2018; Creutzig et al. 2019; (Breyer et al. 2019; Realmonte et al. 2019; Chapter 7; Chapter 12).

Both BECCS and DAC are anticipated to be deployed on the demonstration scale (Daggash et al. 2019; Creutzig et al. 2019a), but they are integrated differently into the energy systems. Biomass and biomass-derived fuels are versatile energy carriers capable of substituting or solid, liquid, and gaseous fossil fuels. Biofuels may prove particularly valuable in sectors that are not amenable to the use of electricity, such as aviation and freight transport. The potential for BECCS is largely dependent on the biomass supply chain. Large land areas would be required to produce bioenergy at scale, which could have an impact on food production and biodiversity due to limited availability of land (Section 6.4, Chapter 7). DAC requires extensive energy inputs and involves high capital costs. Energy systems based on nuclear or thermal power plants with CCS, coupled with DAC could deliver low carbon electricity (Creutzig et al. 2019a). Alternative options include coupling variable renewable energy sources with DAC to produce great greater grid flexibility and to take advantage of excess power production. A portfolio of these technologies could be an option to deliver negative emissions at scale (Daggash et al. 2019).

Box 6.10 Taking Stock of the Energy System Transition

The Global Stocktake is a regularly occurring process under the UNFCCC in which efforts will be made to understand progress on, among other things, global mitigation. Collective progress of countries towards the Paris Agreement goal will be assessed and ways to close any remaining gap between countries' Nationally Determined Contributions (NDCs) and the goal will be sought. What are the most important indicators to understand energy system mitigation progress?

CO_2 emissions from fuel combustion are the bottom line on energy system progress. Beyond CO_2 emissions, primary energy demand by energy sources, final energy consumption by sectors, and total electricity demand provide a first order assessment of the energy system transition. The year at which CO_2 emissions peak is also important. The Kaya Identity can be used decompose energy system CO_2 emissions into carbon intensity of the energy system (CO_2 emissions from fossil-fuel combustion and industry divided by energy use), energy intensity (energy use divided by economic output), and economic output. The impacts of energy and climate policy are reflected in the changes of carbon intensity and energy intensity. Carbon intensity captures decarbonisation of energy supply systems, for example through fuel switching from fossil fuels to non-fossil fuels, upscaling of low carbon energy sources, and deploying carbon dioxide removal technologies. The carbon intensity of electricity is also important, given the role of the electricity sector in near-term mitigation. Economy wide energy efficiency represents efforts of demand-side energy, such as energy conservation, increase of energy performance of technologies, structural change of economy, development of efficient urban infrastructure and increase in electrification of energy end use.

Beyond these aggregate indicators, a second order assessment would explore measures such as the electrification rate, share of renewables, nuclear, CCS or other low carbon technologies in electricity generation, and number of EV or PHEV. Consumption of coal, oil and gas, captures the underling factors of CO_2 emissions. The emphasis of these indicators could differ across countries in the context of national specific circumstances. Carbon prices, fuel prices, energy taxes, and energy subsidy could be candidates to indirectly assess the level of climate policy stringency. Technology- or project-based statistics is also useful to check the progress of transition, for example, the number of CCS facilities.

A critical challenge in the assessment of energy sector progress how to measure societal, institutional, and political progress. These factors are difficult to quantify, yet they are fundamental determinants of the ability to reduce emissions. Public opinion, special interest politics, implications of mitigation for lost fossil jobs, energy subsidies, and energy policies are all critical indicators of progress. In addition, while much of the literature focuses on national level action, mitigation is increasingly being led by cities, states, provinces, businesses, and other subnational or non-national actors. Understanding the progress of these actors will be critical to assess energy system mitigation progress. New research is needed to better assess these "societal" indicators and to better understand the role of non-national actors in mitigation progress.

6.7.2 Investments in Technology and Infrastructure

6.7.2.1 Investment needs for low carbon energy systems

Limiting the temperature rise to 1.5 °C would require a rapid expansion of investment in energy supply, from the current USD 1.8 trillion yr^{-1}, to USD 2 -3 trillion yr^{-1} in 2030, to USD 2.5 -4 trillion yr^{-1} in 2050 (Figure 6.31). Limiting warming to 2 °C calls for gradually increasing investment, reaching USD 1.5 -2.5 trillion $yr\text{-}^{1}$ in 2030 and USD 2.5 -3.5 trillion yr^{-1} in 2050 (Figure 6.31). Investment will need to be maintained in the second half of the century. (*medium confidence*)

Total investments in the global energy system was over USD 1.8 trillion in 2018, representing over 2% of global gross domestic product (GDP) and 8.6% of gross capital formation. Fossil-fuel related investment, including oil, gas, and coal extraction plus fossil-fuel based generation, constituted the majority of the investment amounted to USD 0.93 trillion. Renewable-related investment was about USD 0.33 trillion. Current global investment in low-carbon energy, including efficiency, and electricity networks is around USD 0.9 trillion yr^{-1}. This will need to be expanded significantly to limit warming to 2°C or 1.5 °C (IEA 2019a).

Global energy investment will need to increase to meet rising energy demands from a growing and wealthier global population. There is a wide range in the evaluation of the amount of low-carbon energy investment because the future cost of the technology involves great uncertainty and the amount and composition of the low carbon technology needed to achieve the temperature target varies across models. McCollum et al. (2018b) surveyed over 240 scenarios and found that average annual energy investment needs over the 2016-2050 period in those scenarios would be about USD 2.5 (1.9-3.0) trillion yr^{-1} assuming no additional efforts to address climate change beyond those of today. On the other hand, limiting temperature change to 1.5°C would require USD 3.4 (2.4-4.7) trillion from 2020 through 2050, and USD 3.0 (2.1-4.1) trillion investment needs annually for the 2 °C. They are larger by 22% and by 36% respectively compared to the investment needs in the baseline scenario. Gielen et al. 2019 estimated overall energy investment requirements for the transition to a low-carbon energy system to be about USD 3.43 trillion yr^{-1} from 2015–2050 on average with USD 0.77 trillion of the incremental investment associated with the transition (Gielen et al. 2019). According to (IEA 2019) energy investment needs to limit warming to well-below 2 °C will be USD 3.2 trillion each year from 2019 to 2040 on average, increasing by more than 70% from today, although part of this additional investment is counterbalanced by reduced fuel costs (IEA 2019).

Reducing CO_2 emissions from the energy system will require increased power sector investment. As the share of variable renewable energy generation such as wind and PV increase, it will be necessary to increase investment in the grid to integrate these sources. Therefore, changes to the investment portfolio will be required in addition to scaling up investment in the energy supply sources. If warming is only limited to over 2.5°C, energy supply investment in upstream fossil fuel extraction will continue to expand in order to meet growing energy demand. Investment in thermal power will also keep increasing. In contrast, if the temperature increase is limited to 1.5 °C (2°C), investment in 2030 in upstream fossil fuels and thermal power will be about USD 0.35 (0.25) trillion less than in 2010, while investment in non-fossil fuel power generation will be USD 0.75 (0.7) trillion more and investment in the grid will be USD 0.55 (0.5) trillion greater (Figure 6.32). IEA (2019) supports the importance of electricity investment. In that analysis, the largest increase in supply side investment comes from renewables-based power generation, which adds up to USD 0.5 trillion each year over the period between 2019-

2030 and over USD 0.7 trillion between 2031-2040 respectively. Investment in fossil fuel power generation still continues, but about half of this spending is associated with CCUS technologies.

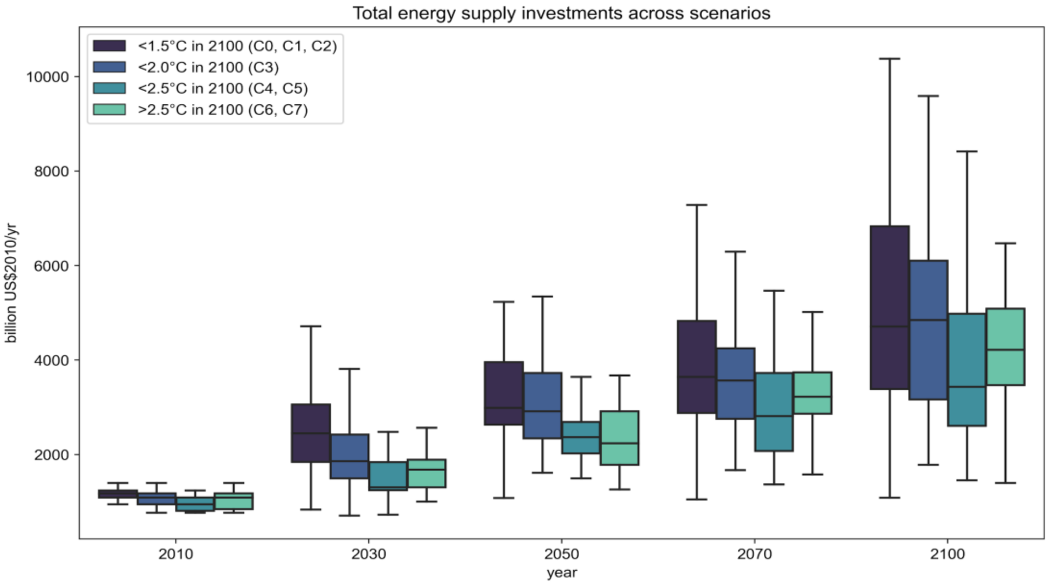


Figure 6.31 Total energy supply investments across scenarios (Source: AR6 Scenario Database)

Shifting energy investment portfolio for delivering rapid decarbonisation in the economy could have global distributional impacts. It will entail a major job reallocation from emission-intensive sectors to low-carbon industries (McCollum et al. 2014);. A broad array of technology, labor, and industry policies would be a key to deliver a just transition.

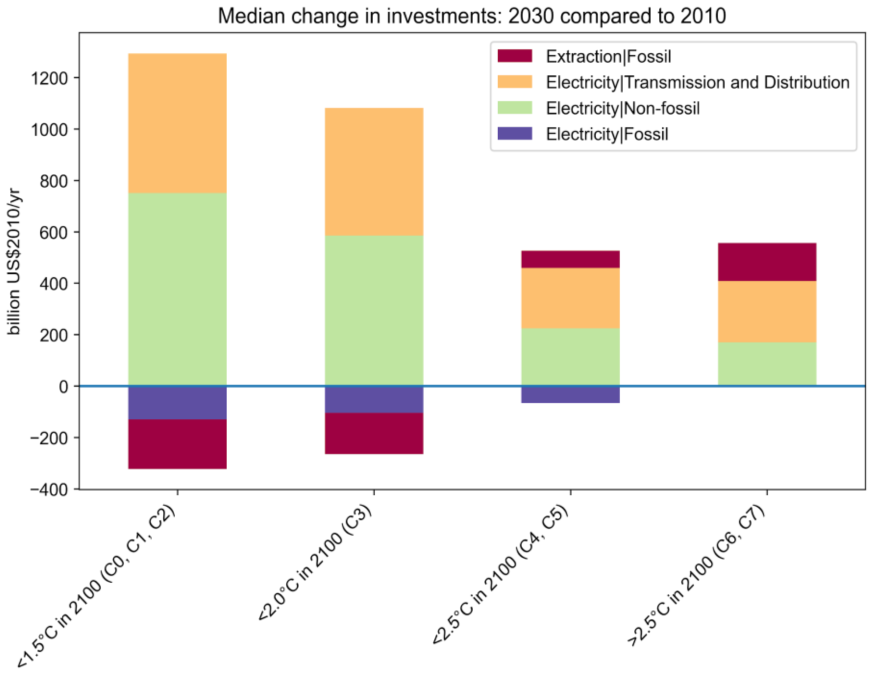


Figure 6.32 Change in investment profile, 2030 compared to 2010. (IPCC Scenario Database)

All regions will need to increase clean energy investment, but changes in investment patterns will vary by region (*high confidence*). In Latin America, the Middle East, and Africa, the stringency of climate targets will not change the total amount of energy investment significantly, but the investment portfolio will shift. In contrast, in OECD countries and Asia, more ambitious climate goal not only change the investment portfolio, but also increase the overall amount of energy investment (Figure 6.33; Sun et al. 2019). There are important differences across countries in terms of basic energy needs, energy supply structures, and consumption patterns. These are responsible for the divergence in their investment landscapes and associated needs (IEA 2019). Currently 90% of energy investment is concentrated in high- and upper-middle income countries, but investment needs to grow in the fast-growing lower-middle and low-income countries. The investment to ensure universal energy access, especially for electricity access, could amount to USD 45 billion yr^{-1} between 2019 and 2030 (IEA 2019). Low energy expenditures are associated with high and increasing economic growth rates (Fizaine and Court 2016; Zhou et al. 2019). Investments in efficiency are important to minimise energy expenditures without hindering economic development.

The low-carbon transition will require a large-scale mobilisation of all sources of investment. Given the size of the investment, low-carbon energy investments need to be financed through decarbonising the economy-wide infrastructure investment. Increasing low carbon investment primarily requires shifting existing capital investment (McCollum et al. 2018a), rather than creating new pools of capital. In light of the current annual fixed capital investment of USD 26.7 trillion, the investment gap is not due to lack of capital in the global economy and could be covered by shifting existing capital investment to low-carbon investment. Low carbon energy systems will require significant investment, but this is a part of the fixed capital formation investment in the landscape of the economy (Granoff et al. 2016).

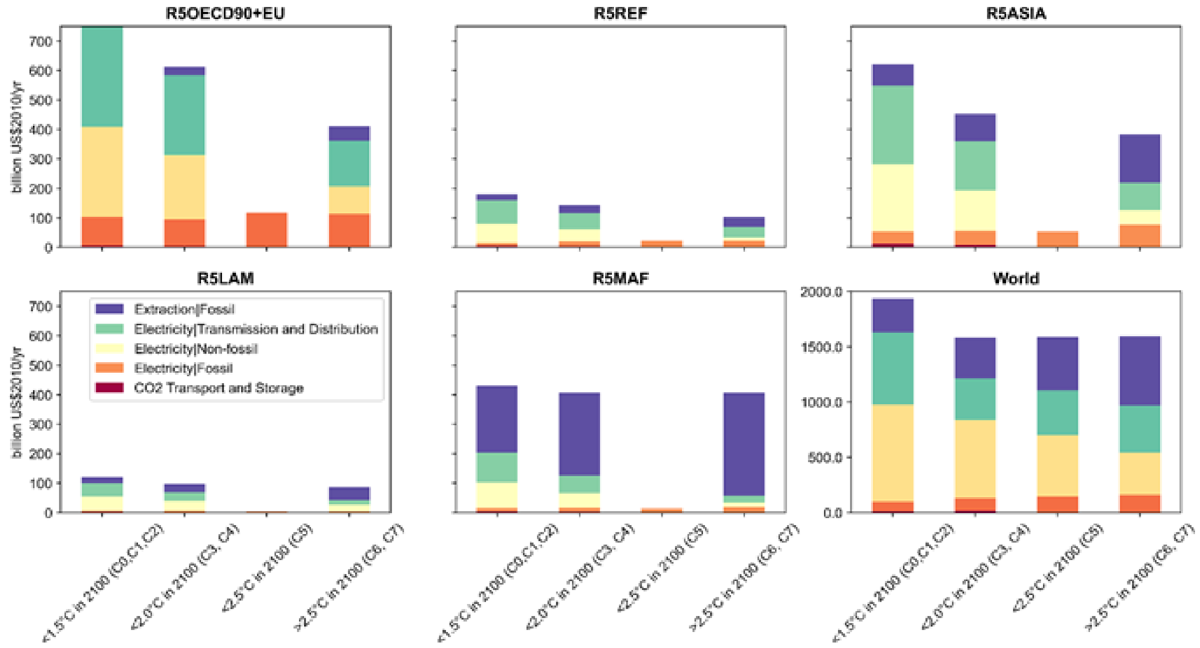


Figure 6.33 Annual average energy investment by region (IPCC Scenario Database)

Private sector investment is essential to scale up low-carbon investments. This will require removing barriers and creating an enabling environment (*high confidence*) (Chapter 15; Zhou et al. 2019). In order to mobilise private capital, development of attractive conditions for low-carbon investments is crucial, especially in countries where investment risks are high (Schmidt 2014). Addressing investment barriers to facilitate access to financing for climate technologies is also required. There is a wide range of barriers to low-carbon investment, including currency and political risks, competition with other investment needs, and lack of knowledge. Removing these barriers will help mobilise finance (Hafner et al. 2019). Low-carbon energy investments are usually risk sensitive. Climate policy would decrease such downside risks and would help redirection of investment flow from fossil fuels to renewables. Private funding is very sensitive to risks, such as market distortion, currency risk that may create unpredictable losses, and political instability, so de-risking is effective in expanding investment in low-carbon technologies (Waissbein et al. 2013; Steckel and Jakob 2018). Renewable energy technologies are much more sensitive to the increase in financing costs because renewable energy sources, such as concentrated solar power, photovoltaic, wind, are highly capital intensive, while fossil fuel-based plants are dominated by fuel cost (Schmidt 2014).

Despite huge variation in risk profiles across countries, most of the integrated assessment models assume uniform investment risks. If non-uniformities in investment risks are taken into consideration, mitigation costs could be more expensive than it would be in a world with uniform investment risks (Akimoto et al. 2012). Heterogeneity of risks across regions and technologies has a considerable impact on the assessment of investment profiles. Iyer et al. (2015) found that non-uniformities in investment risks lead to a 36% reduction globally in investments in low-carbon technologies whereas fossil-fuel investments increase by 11%.

6.7.3 Energy System Lock-In and Path Dependence

Path dependence is defined as inertia to large-scale changes by resistance due to favorable socio-economic conditions. Carbon lock-in is a specific case of path dependence (Seto et al. 2016). Given that energy system mitigation will require a major course change from recent history, lock-in is an important issue for energy system mitigation. While lock-in is typically expressed in terms of physical infrastructure that would need to be retired early to reach mitigation goals, lock-in, in reality, involves a much broader set of issues that move beyond physical systems and into societal and institutional systems (Table 6.10).

Table 6.10 Lock-in types and typical mechanisms (Kotilainen et al. 2020)**.** Reproduced under Creative Cotablemmons 4.0 International License.

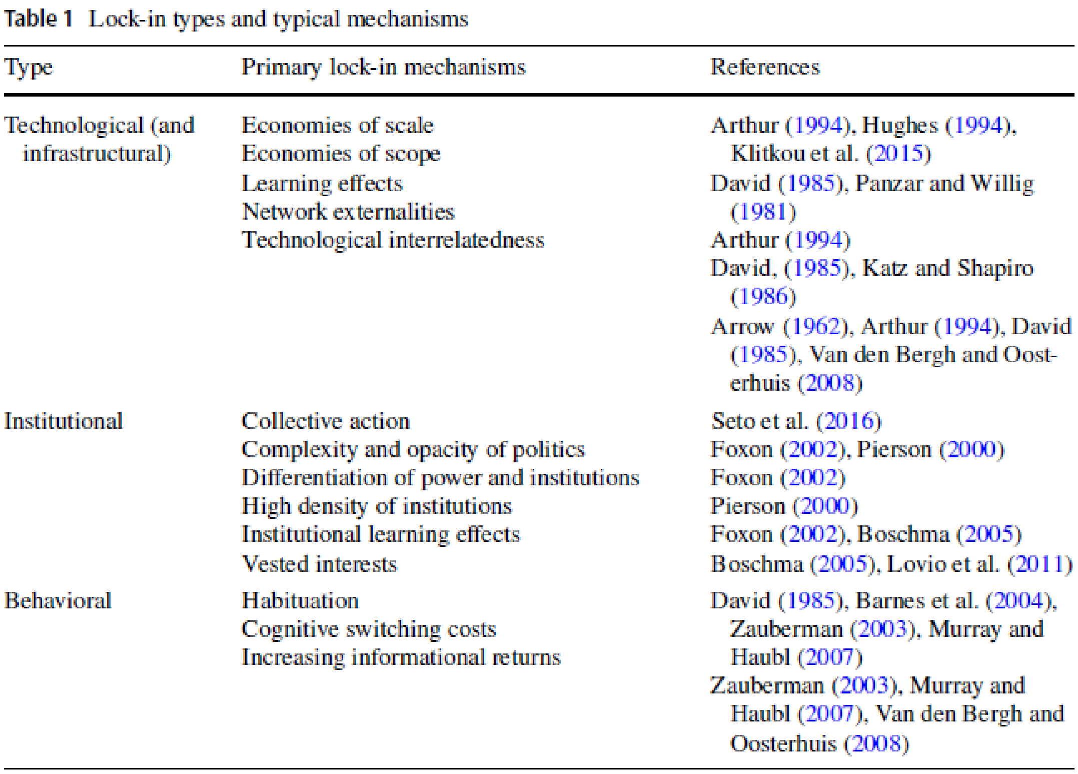


Table 1 Lock-in types and typical mechanisms

Type	Primary lock-in mechanisms	References
Technological (and infrastructural)	Economies of scale	Arthur (1994), Hughes (1994), Klitkou et al. (2015)
	Economies of scope	David (1985), Panzar and Willig (1981)
	Learning effects	Arthur (1994)
	Network externalities	David, (1985), Katz and Shapiro (1986)
	Technological interrelatedness	Arrow (1962), Arthur (1994), David (1985), Van den Bergh and Oosterhuis (2008)
Institutional	Collective action	Seto et al. (2016)
	Complexity and opacity of politics	Foxon (2002), Pierson (2000)
	Differentiation of power and institutions	Foxon (2002)
	High density of institutions	Pierson (2000)
	Institutional learning effects	Foxon (2002), Boschma (2005)
	Vested interests	Boschma (2005), Lovio et al. (2011)
Behavioral	Habituation	David (1985), Barnes et al. (2004), Zauberman (2003), Murray and Haubl (2007)
	Cognitive switching costs	Zauberman (2003), Murray and Haubl (2007), Van den Bergh and Oosterhuis (2008)
	Increasing informational returns	

6.7.3.1 *Societal and Institutional Inertia*

A combination of demand-side factors - user, business, cultural, regulatory, and transnational - hinder energy transitions consistent with 2/1.5°C. Strong path dependencies – even in early formative conditions – can exercise lasting impacts on energy systems, producing inertia, which can cut across technological, economic, institutional and political dimensions (*high confidence*) (Vadén et al. 2019) (Rickards et al. 2014).

Energy systems are paradigmatic of the ways in which massive volumes of labor, capital, and effort become sunk into particular institutional configurations (Bridge et al. 2013; Bridge et al. 2018). A number of embedded factors affect large-scale transformation of these systems and make technological diffusion a contested process:

- **User environments** affect purchase activities and can involve the integration of new technologies into user practices and the development of new preferences, routines, habits and even values (Kanger et al. 2019).
- **Business environments** can shape the development of industries, business models, supply and distribution chains, instrument constituencies and repair facilities (Béland and Howlett 2016)(.
- **Culture** can encompass the articulation of positive discourses, narratives, and visions that enhance cultural legitimacy and societal acceptance of new technologies. Regulatory embedding can capture the variety of policies that shape production, markets and use of new technologies, e.g. safety regulations, reliability standards, adoption subsidies, demonstration projects, and infrastructure investment programs.
- **Transnational community** can reflect a shared understanding in a community of global experts related to new technologies that transcends the borders of a single place, often a country.

While radical low carbon innovation involves systemic change (Geels et al. 2018), these are typically less popular than energy supply innovations among policymakers and the wider public. Managing low carbon transitions is therefore not only a techno-managerial challenge (based on targets, policies and expert knowledge), but also a broader political project that involves the building of support coalitions that include businesses and civil society (moderate evidence, high agreement).

Radical low carbon innovation involves cultural changes extending beyond purely technical developments to include changes in consumer practices, business models, and organisational arrangements. The development and adoption of low-carbon innovations will therefore require sustained and effective policies to create appropriate incentives and support. The implementation of such policies entails political struggles because actors have different understandings and interests, giving rise to disagreements and conflicts.

Such innovation also involves pervasive uncertainty around technical potential, cost, consumer demand, and social acceptance. Such uncertainty carries governance challenges. Policy approaches facing deep uncertainty must protect against and/or prepare for unforeseeable developments, whether it is through resistance (planning for the worst possible case or future situation), resilience (making sure you can recover quickly), or adaptation (changes to policy under changing conditions). Such uncertainty can be hedged in part by learning by firms, consumers, and policymakers. Social interactions and network building (e.g. supply and distribution chains, intermediary actors) and the articulation of positive visions, such as in long-term, low-emission development strategies, all play a crucial role. This uncertainty extends to the impacts of low carbon innovations on energy demand and other variables, where unanticipated and unintended outcomes are the norm. For instance, rapid investments in public transport networks could restrict car ownership from becoming common in developing countries (Du and Lin 2017).

6.7.3.2 Physical Energy System Lock-In

Continued exploration of fossil fuels, as well as commissioning of infrastructure reliant on it has overcommitted 500-700 Gt-CO_2 and created significant risks for limiting warming to 1.5°C or 2°C (Callaghan 2020) (*high confidence*). These combined with emissions from proposed infrastructure exceed emissions required to limit warming to 1.5°C (*medium confidence*). The largest segment of committed emissions from existing infrastructure is from coal and gas fired power plants which account for 200-300 Gt-CO_2 (Tong et al. 2019; Smith et al. 2019). The lifetime of these plants is also high i.e. 40-50 years, creating long lasting risks to climate goals (Erickson and Tempest 2015). Industry sector lock-in amounts for >100 Gt-CO_2 while buildings and transport sector together contribute another 50-100 Gt-CO_2.

Lock-in is also important for fossil fuel resources. Both coal and gas exploration have continued, and new permits are being issued, which may cause economic (Erickson et al. 2018) as well as non-economic issues, such as legacy methane emissions (Boettcher et al. 2019). It is projected that higher-cost, yet-to-produce resources, are most likely to increase carbon lock-in. This would likely lead to further scale-back of capital-intensive oil investments and especially to a substantial scale-back of capital investment in onshore tight oil production (Erickson et al. 2015).

While the power sector is a larger source of carbon lock-in, lock-in in urban and transport sectors are significantly more complicated due to strong socio-institutional effects. Long-term improvements would entail significant non-technological challenges as well with behavioral change issues (interaction of market, industry and society). This is important to consider since urban infrastructure will commit roughly 14 Gt-CO_2 annually (Erickson and Tempest 2015). Broadly, urban environments involve infrastructural, institutional, and behavioral lock-ins (Ürge-Vorsatz et al. 2018).

Carbon is unevenly distributed. China alone accounts for around 40% of the world's committed emission from infrastructure, with the US, India and EU accounting for roughly 15% each (*high confidence*). Four mature industrialised countries - USA, EU, Japan, and Australia - together account for around a third of committed emissions, even though their share in current annual CO_2 is much greater. The disproportionately high share of committed emissions in emerging economies is due to fast growth in recent years resulting in a comparably young fossil-based infrastructure system with substantial remaining lifetime (Shearer et al. 2017). Mature industrialised countries tend to have older infrastructures, part of which will be up for renewal in the near future (Tong et al. 2019). Coal-fired power plants currently planned or under construction are associated with an additional ~300 Gt-CO_2, of which ~75% and ~10% are located in Asia and the OECD respectively (Pfeiffer et al. 2018)

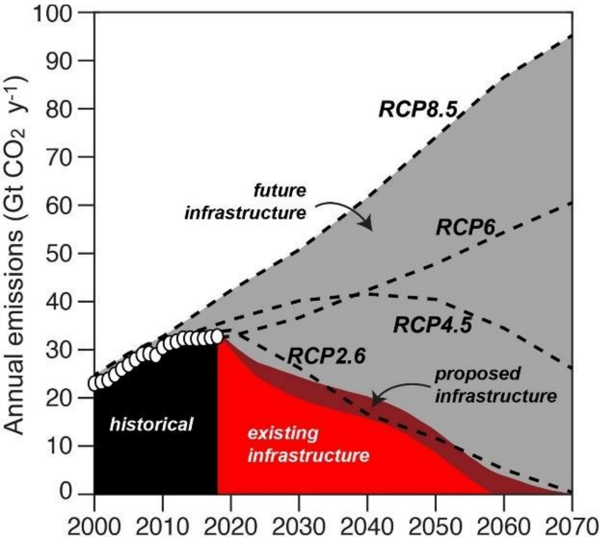


Figure 6.34 Annual emissions from existing, proposed and future infrastructure (Tong et al. 2019).

Despite projected needs to reduce fossil fuel usage and the multi-faceted benefits arising out of proposed coal phaseout plans (Liu et al. 2019a; Portugal-Pereira et al. 2018; Rauner et al. 2020), both coal and gas power plants have continued to be commissioned globally (Jewell et al. 2019; Jakob et al. 2020;

Section 6.3), most notably in China and other Asian countries. In many regions, they exceed the needed capacity (Shearer et al. 2017).

Existing policies and the NDCs are insufficient to prevent a further increase of locked-in carbon (*high confidence*) (Bertram et al. 2015; Johnson et al. 2015; Luderer et al. 2018). Designing policy to prevent lock-in requires accounting for the role of time; that is incorporating the differences between short-term and long-term interventions. Delays in mitigation will exacerbate lock in and could result in large-scale stranded assets from early retirement if stringency is subsequently increased (Box 6.11). Near-term implementation of stringent GHG mitigation policies and risk-free returns to business investments are likely to be most effective in dealing with carbon lock-in Haelg et al. 2018. Accordingly, current investment decisions are critical because there is limited room within the allotted carbon budgets of 1.5°C and 2°C (Rosenbloom 2019; Kalkuhl et al. 2019). This is because individual interventions that might enable behavioral changes in the short-term need to be compatible with larger industrial scale policy changes (Seto et al. 2016). Such policies should also consider different energy transition strategies as a result of different resources and carbon budgets between countries (Bos and Gupta 2018; Lucas 2016).

Near-term policy choices are particularly consequential for fast-growing economies. For the example of India, (Malik et al. 2020), exploring scenario results from national and global models, show that coal capacity in India is expected to increase until 2030, along with rapid deployment of wind and solar PV power. However, 133-237 GW of coal capacity would be stranded after 2030 if India were to pursue an ambitious climate policy in line with a well-below 2°C target. In China, Wang et al. 2020a showed that 930 GW of coal power plants would need to be retired early in a scenario that starts from the NDC in 2030 and transitions to a 2 °C compatible pathway thereafter. In Latin America, the comparable result is 6.9 Gt CO_2 when counting all existing power plants, and another 6.7 Gt when adding all announced, authorised, and procured power plants up to 2060 (González-Mahecha et al. 2019) . A number of strategic choices may be made to reduce the carbon lock-in within large-scale infrastructure such as power plants, including reducing fossil fuels subsidies (Box 6.3), building CCS-ready facilities, or ensuring that facilities are appropriately designed for fuel switching (Budinis et al. 2018). Substantial lock-in may necessitate considerable deployment of CDR to compensate for high cumulative emissions.

Past and present energy sector investments have created technological, institutional and behavioral path dependencies aligned towards coal, oil, and natural gas (*high confidence*). Moving away from these will require financial investments as well as socio-political reforms for carbon mitigation, which may include reduction of fossil fuel subsidies (that are 5%+ of the global GDP) or creating societal readiness towards electric vehicles (Fouquet 2016). In several emerging economies, large projects are planned that address poverty reduction and economic development. For instance, economic development without dedicated policies will inevitably lead to large coal infrastructure in Sub-Saharan Africa (Steckel et al. 2020; Joshua and Alola 2020)(. Similarly, a majority of COVID-19 recovery funds are apportioned to fossil fuels (SEI 2020). These new path dependencies may create short-term effects such as energy resilience, reduced cost of electricity and high employment rate (Rauner et al. 2020; Patrizio et al. 2018). In the longer term, this will lead to carbon lock-in. Moreover, several coal mining communities, have significant health and economic burdens thus creating incentives for decarbonisation. This demonstrates that path dependencies have more sustainability effects than simply carbon emissions. (see Box 6.2 and Section 6.7.7).

Box 6.11 Stranded Assets

Stranded assets can be broadly defined as assets which "suffer from unanticipated or premature write-offs, downward revaluations or [conversion] to liabilities." In the context of climate change mitigation, the shift in the methods of energy production from carbon-intensive to low-carbon or zero-emission sources shift could result in the stranding of carbon-intensive assets before the end of their expected lifetime. The issue of stranded assets is important because they could create risks for financial market stability which in turn could create risks for macro-economic stability (Mercure et al. 2018). Additionally, stranded assets could also result in a rapid loss of wealth for the owners of affected capital assets, potentially creating political economy risks including avoidance of mitigation action (Vogt-Schilb and Hallegatte 2017, Ploeg and Rezai 2020). Stranded assets could manifest themselves in two forms: fossil-fuel resources that cannot be burned, and premature retirement of man-made capital assets (e.g. power plants) due to climate policies.

If warming is to be restricted to 2°C, about 30% of oil, 50% of gas, and 80% of coal reserves will remain unburnable (Meinshausen et al. 2009, Leaton 2011; Leaton Ranger 2013; McGlade et al. 2015; Bauer et al. 2016; Pye et al. 2020; IRENA 2017) (*high confidence*). Significant stranding of energy reserves would occur in countries that have large oil, gas and coal reserves such as Australia, Brazil, Canada, Indonesia, Mexico, the Russian Federation, Saudi Arabia and South Africa IRENA 2017). High stranded asset risks have also been suggested for Chinese coal production, and the crude oil sector in the Middle East and Latin America (Ansari and Holz 2020).

In addition, restricting warming to 2°C could require premature retirements of fossil fuel power plants of about 200 GW per year globally after 2030 even if countries were to achieve their NDCs as stated (Iyer et al. 2015; Johnson et al. 2015; Iyer et al. 2015b; Fofrich et al. 2020) (*high confidence*). Consequently, coal- and gas-fired power plants need to retire respectively about 25 and 30 years earlier than historically has been the case to limit warming to 2°C and 1.5°C (Cui et al. 2019; Fofrich et al. 2020). Since the economic value of capital depreciates over its lifetime, the risks of stranded power plants are greatest in countries with large amounts of newer fossil infrastructure. In China and India, the power sector is expected to have the largest share (about 50%) of total stranded asset value while stranding is expected to be concentrated in the buildings sector for developed countries (IRENA 2017).

The combined economic impacts of stranded fossil fuel resources and capital could amount to trillions of dollars (*high confidence*) (Battiston et al. 2017, Sen and von Schickfus 2020, Binsted et al. 2020). This could resulting in a cumulative discounted global wealth loss of USD 1–4 trillion between 2015 and 2050 (Mercure et al. 2018) and a cumulative undiscounted loss of USD 10-20 trillion during the same period (*medium confidence*) (IRENA 2017). Stranded assets could also imply challenges for investment needs – especially in the power sector – as premature retirements of fossil fuel power plants would need to be accompanied by deployment of low-carbon technologies to meet demand. Limiting long-term warming to 2°C could require about a USD 1 trillion of power sector capital investments per year globally beyond 2030 which is about four times the rate of investments observed historically (Iyer et al. 2015;; Eom et al. 2015; McCollum et al. 2018; Kriegler et al. 2013). Limiting long-term warming to 1.5°C could require even faster rates of investment – up to an additional USD 1 trillion yr^{-1} (McCollum et al. 2018b).

Stranded asset risks could be reduced by strengthening mitigation in the near-term as fossil fuel based energy production would decrease under strong near-term mitigation policies and hence, there would be fewer assets to strand in the future (Johnson et al. 2015; Bertram et al. 2018) (*high confidence*). Strengthening the NDC pledges could decrease stranded assets in the power sector by more than 50% (Iyer et al. 2015). In contrast, if countries delay mitigation and do not achieve their NDCs, catching up with cumulative emissions budgets beyond 2030 could result in up to double the stranding – corresponding to about 9 trillion (undiscounted, cumulative from 2015 to 2050) worth of additional stranded assets – compared to a scenario in which countries achieve their NDCs as stated (Iyer et al. 2015; Kriegler et al. 2013; Binsted et al. 2020; IRENA 2017).

Stranded asset risks could also be reduced by retrofitting fossil fuel based power plants with CCS. It has been suggested that CCS could reduce hundreds of gigawatts stranded assets (Clark and Herzog 2014; Fan et al. 2018; Iyer et al. 2017). However, while the ability to deploy CCS at scale remains uncertain, deploying large amounts of CCS – particularly with bioenergy – could create a number of tradeoffs (Calvin et al. 2014).

6.7.4 Fossil fuels in transition

Global fossil fuel use will need to decline by an average of around 6%/year through 2050 to limit warming to 1.5°C (*medium confidence*); this will require a reversal in investment and construction patterns for coal, oil and gas (*high confidence*). Fossil fuels account for about 80% of primary energy today. In 1.5°C and 2°C scenarios, fossil energy provides around 38% (28-53%) and around 55% (41-73) in 2050 (AR6 database). The timeline for reducing production and usage varies across different fossil fuels due to their different carbon intensities and the different applications in which they are used. Construction of new coal infrastructure may jeopardise achieving the 1.5°C target (Spencer et al. 2018). Compared to coal, oil and gas extraction is more profitable and capital-intensive. This is why strong financial interests pose barriers and keep capital-intensive oil resources in production, even if policy efforts and social organisations call for a transition away from oil (Erickson et al. 2017).

There is large ambiguity in the extent to which fossil fuels with CCS would be compatible with the 2°C and 1.5°C targets (*medium confidence*). As inclusion of CCS increases, the share of fossil energy use increases under stringent climate restrictions while the GDP losses also reduce (Muratori et al. 2016; Marcucci et al. 2019). However, there is lack of consensus on the degree to which CCS could delay fossil fuel phaseout in 2/1.5°C transitions. While some studies show fossil fuels with CCS to be significant in energy mix by 2050 (Koelbl et al. 2014; Eom et al. 2015)(Vishwanathan and Garg 2020), others show that unabated coal retirement far outpaces the deployment of coal with CCS (Budinis et al. 2018; Xie et al. 2020) Moreover, several models also project that with availability of CO_2 capture technology, BECCS might become significantly more appealing than fossil CCS even before 2050 (Luderer et al. 2018).

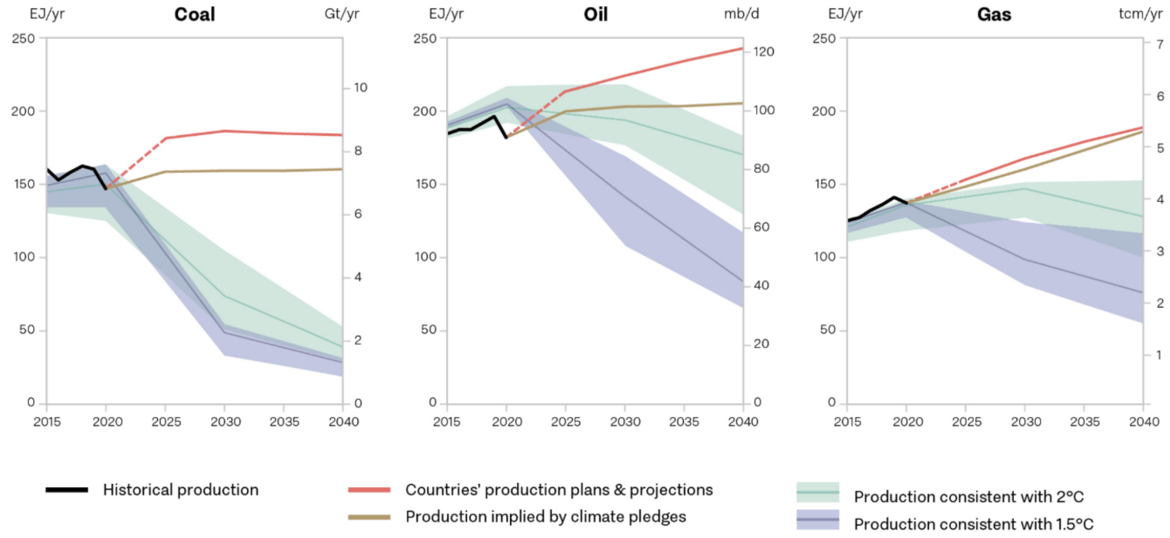


Figure 6.35 Mid-century pathways for fossil fuel phaseout (SEI 2020)

Global coal consumption needs to be largely eliminated by 2040-2050 to limit warming to 1.5°C, and 2050-2060 to limit warming to 2°C (*high confidence*). Any new coal infrastructure beyond 2025 would likely be inconsistent with 1.5°C targets (*high confidence*). Coal use is anticipated to decline in the US and Europe with complete phaseout likely before 2035 based on other sources becoming more economic (Oei et al. 2020); Grubert and Brandt 2019;. In several developing economies, the low age of the electricity fleet would make a complete phaseout before 2050 cost-prohibitive (Garg and Shukla 2009;

Jewell et al. 2016). There are considerable differences in projected coal phaseout timelines in major Asian economies. Some studies suggest that coal may continue to be a part of the Chinese energy mix composing around a third of the total primary energy consumption by 2050 in 2°C scenario (He et al. 2020). Others indicate that a strategic plant-wise transition would decrease the risk of stranded assets and enable a near-complete phaseout by 2050 (Wang et al. 2020a; Cui et al. 2020); This would entail prioritising earlier retirements of plants based on technical (efficiency), economic (profitability, local employment) and environmental considerations (e.g. water scarcity for cooling).

Natural gas may be a part of near-term transition solutions, especially in developed economies, both for electricity generation and in liquefied forms (*medium confidence*). Compared to coal, there is greater flexibility for the phaseout of natural gas power plants with projected peak year around 2050 and 2035 for the 2°C and 1.5°C target respectively (*medium confidence*). In parts of the world, natural gas use may continue to increase with peaking year around 2050 for 2°C scenarios especially with availability of CCS (McJeon et al., 2021). Under 1.5°C constraints, overall decline in gas use is observed by 2030-2035 when retirements in the developed world outweigh new infrastructure in the developing world (SEI 2020). There is variability in the role gas would play in future scenarios based on national climate commitments and availability of cheap renewables. In the EU, for example, gas would have to make place for the increasing share of renewables (Vrontisi et al. 2020), while in India, natural gas replaces coal, being seen as the transition fuel for 2020-2030 (Vishwanathan and Garg 2020; Malik et al. 2020)(in 2°C scenario. Note that these differences are not only present in the power sector but also in other end-use. Considerable growth is projected in the liquefied natural gas (LNG) market especially with the developments in transnational natural gas pipelines (Vivoda 2019; Gan et al. 2020).

The phaseout of oil will likely be slower than coal and gas (*medium confidence*). The transport sector will continue to be 60-90% oil-based in 2°C scenarios and 40-70% oil-based in 1.5°C scenarios by 2050 owing to fewer low-carbon alternatives (*medium confidence*). While oil use is projected to decline immediately in the 1.5°C scenarios, it will still have significant presence till 2050. Oil use continues to be the significant source of transport fuels in most 2°C scenarios (McGlade and Ekins 2015a). In the U.S., oil use may reduce to about half of the current levels as a transport fuels (Feijoo et al. 2020) under 2°C constraints. In other parts of the world, this decline is much slower with peak occurring around 2035 in China and Latin America (Delgado et al. 2020; Pan et al. 2020). This is because of the higher cost of producing liquid transport fuels from other sources such as biomass (6.4.2.6). Moreover, the presence of electric vehicles affects oil demand to a limited extent as their role is limited to the LDV and HDV categories.

6.7.5 Policy and Governance

Policy and governance frameworks are essential for shaping near and medium term energy system transitions (*high confidence*). While policy interventions are necessary to achieve policy goals and address market failures appropriate governance frameworks are crucial to ensure policy implementation (*high confidence*). The policy environment in energy transition pathways relate to climate policy goals, the characteristics of the policy regimes and measures to reach the policy goals including implementation limits and obstacles, and the timing of the climate instrument (Kriegler et al. 2014b)

In the academic literature, a broad set of policy approaches is discussed. Research in environmental economics focuses mainly on market-based approaches as the least-cost policy to achieve emission reductions (Kube et al. 2018). Many countries, however, have implemented policy mixes with a diverse set of complementary policies to achieve their energy and climate policy targets. One example is the German Energiewende with – among other things – a substantial support system for renewables, an action plan for energy efficiency and phase out decisions for nuclear- and coal-based power generation next to the EU Emissions Trading Scheme (Löschel et al. 2019). Another example is the history of decarbonisation efforts in the United Kingdom (see e.g. Fankhauser 2013; .Wilson and Staffell 2018).

More general, the NDCs under the Paris Agreement are all characterised by fragmented climate policy mixes.

These policy mixes (or policy packages) are shaped by different factors, including policy goals and objectives (including political, social and technological influences), multiple market, governance or behavioral failures or previous policy choices of earlier policy eras (Rogge 2017). With pursuing multiple policy goals or targeting some type of imperfection, well designed policy mixes can in principle reduce mitigation costs or increase welfare (Corradini et al. 2018). For example, the interaction between carbon pricing and the support for clean energy technologies in the EU clean low-carbon strategy for 2050 can reduce mitigation costs and allow for the early adoption of more stringent climate targets (Vandyck et al. 2016). However, current policy efforts to promote adoption of low-carbon technologies focus mainly on economic incentives but policies can be more cost-effective when they would also target relevant cognitive and motivational factors (Mundaca et al. 2019).

In the future, well-designed policy mixes will support the pursuit of multiple policy goals and target effectively different types of imperfections and framework conditions. Coordinated, coherent, and consistent policy mixes will take into account the technological, economical and societal situation (*high confidence*). Several issues are important in the transition to net-zero energy systems. Different development stages of new technologies have to be considered (Graaf and Sovacool 2020). For prototype technologies and technologies in the demonstration phase, research subsidies and demonstration projects are of importance. With early adoption technologies, infrastructure development and strengthening of markets are necessary, while with mature technologies the scope is on early retiring or repurposing of existing assets (IEA 2020a). Furthermore, effective policy mixes will address different failures and deal with various uncertainties, e.g. with respect to technological, climate, and socio-economic (feasibility) developments (Aldy 2020) but also with respect to outcomes of individual policies (e.g. Borenstein et al. 2019). Therefore, policy mixes may balance the trade-off between stability and flexibility to changes of individual policies (Gawel and Lehmann 2019), but also in the policy mix over time (Rayner et al. 2017). Some policy instruments may become feasible over time as, e.g., technological advancements reduce transaction cost of comprehensive market-based approaches (Andoni et al. 2019; Di Silvestre et al. 2020).

Interactions between policy measures including their scope, stringency and timing influence the costs of achieving the climate policy goals as well as the achieved emission reductions (Corradini et al. 2018). In particular, some policy instruments may lead to lock-in effects (as discussed in Section 6.7.3.), compete with other regulations (Graaf and Sovacool 2020) or trigger negative policy interactions (Perino 2015; Jarke-Neuert and Perino 2020). However, for information provision, in particular nudges based on social comparisons for energy demand, multiple nudges might lead to only limited crowding out effects (Brandon et al. 2019).

Furthermore, policy mixes often include sector-specific regulation. Compared to economy-wide approaches, sectoral policies may be able to directly target specific sector details. However, limited coordination across sectors (e.g. lack of a comprehensive market mechanism) may lead to efficiency losses (e.g. Rosendahl et al. 2017). These losses may also depend on other policies, such as pre-existing taxes (Goulder et al. 2016; Marten et al. 2018) or research and development policies (Acemoglu et al. 2016). Moreover, unilateral policy mixes may be wary of addressing risks of carbon leakage, while balancing potential issues of (industrial) competitiveness (Martin et al. 2014; (Rosendahl et al. 2017). Energy leakage may become an even more important concern during the transition to a net-zero energy system (e.g., hydrogen and its carbon content). Potential leakage in electricity markets in the context of incomplete emission markets is discussed in many places (Caron et al. 2015; Thurber et al. 2015; Murray and Maniloff 2015; Fell and Maniloff 2017; Duan et al. 2017; Qian et al. 2018). Well-designed policy mixes will hence target the whole life-cycle or value chains, e.g., by policies on limiting fossil fuel extraction (Asheim et al. 2019).

Existing policy mixes emerge out of individual policy interventions and often reflect different political economy constraints and goals. The resulting policy mixes are often not economically optimal in the sense of achieving mitigation goals cost-effectively. However, evaluation of policy mixes requires a broader set of evaluation criteria which reflect different considerations in the transformation of energy systems, such as multiple policy goals and feasibility of policies. (*high confidence*)

Policy mixes might rather emerge than be specifically designed (Howlett 2014; (Rogge 2017)and may reflect differences across jurisdictions and sectors (Howlett 2014). For example, taking into account country-specific objectives, failures, and limitations, carbon prices may be only one part of a broader policy mix and thereby may not be uniform across countries (Bataille 2020). However, this makes it more difficult to assess total abatement cost since costs of complementary policies are often less visible and often address rather high-cost mitigation options (e.g., Borenstein et al. 2019).

Existing policy mixes are difficult to evaluate because they target multiple objectives, and the evaluation must take into account various criteria (outlined in Chapter 13), such as environmental and economic effectiveness, distributional effects, transformative potential, institutional requirements and feasibility. Economic costs for example depend on policy goals and implementation. Existing studies on policy mixes suggest a more comprehensive approach (Rosenow et al. 2017), while also highlighting that an "excessive" amount of instruments may reduce overall effectiveness of the policy mix (Costantini et al. 2017). For the case of innovation, combining environmental regulation and innovation policies may be of particular importance (Fabrizi et al. 2018). Regarding policy mix characteristics, consistency and credibility of policy mixes are positively associated with green innovation (Rogge and Schleich 2018).

Future / prospective policies are difficult to evaluate due to the challenges of implementing individual policies in ex-ante analyses (*high confidence*). Recent ex-ante analyses based on "current policy scenarios" try to implement existing policies besides (implicit) carbon pricing in their models, allowing for example analyses of potential implementation gaps between overarching targets and goals achieved through existing policies (Elzen et al. 2016; Roelfsema et al. 2020; van Soest et al. 2017; Rogelj et al. 2016) However, many ex-ante energy transition pathways are still based on cost-optimal mitigation frameworks (e.g. Vrontisi et al. 2018), with a rather limited analysis of interactions between policy measures. Hence they are often not describing real-world energy transitions properly, but rather differences in implied carbon prices, constraints in technology deployment and timing of policies (Trutnevyte 2016).

6.7.6 Behaviour and Societal Integration

Members of societies, including individuals, civil society, and businesses, will all need to engage with and be affected by energy system transitions. This raises questions about the extent to which different strategies and policy would effectively promote mitigation behaviors and the factors that increase the social acceptability of mitigation options, policies, and system changes.

6.7.6.1 Strategies to encourage climate mitigation actionss

Climate policy would be particularly effective if it targets key factor inhibiting, enabling, and motivating mitigation behaviors. As barriers may differ across mitigation options, regions, and groups, tailored approaches would be more effective (Grubb et al. 2017). When people face important barriers to change (e.g., high costs, legal barriers), policy would be needed to increase the attractiveness of low carbon actions, or to make behavior associated with high carbon emissions less attractive. As people generally face multiple barriers for change, combinations of policies would be more effective (Rosenow et al. 2017).

Financial incentives can enable mitigation actions (Santos 2008; Thøgersen 2009; Eliasson 2014; Maki et al. 2016; Bolderdijk et al. 2011), particularly when mitigation actions are costly (Mundaca 2007). In many countries, more residential solar PV were installed after the introduction of favorable financial schemes such as feed-in-tariffs, federal income tax credits, and net metering (Wolske and Stern 2018). Similarly, a subsidy promoted the installation of solar water heaters in Taiwan (Chang et al. 2009). Yet, financial incentives may underperform expectations when other factors are overlooked. For example, people may not respond to financial incentives when they do not trust the organisation sponsoring the incentive program or when it takes too much effort to receive the incentive (Mundaca 2007; Stern et al. 2016). Financial incentives are more effective if combined with strategies addressing non-financial barriers.

Communicating financial consequences of behavior seems less effective than actually changing financial costs and benefits, and compared to social rewards (Handgraaf et al. 2013) or emphasising benefits of actions for people (e.g., public health, comfort) and the environment (Bolderdijk et al. 2013; Asensio and Delmas 2015; Asensio and Delmas 2016; Schwartz et al. 2015; Ioulia V. Ossokina 2020). Effects of financial appeals may be limited because they make people focus less on environmental consequences, weaken intrinsic motivation to engage in mitigation actions, provide a license to pollute (Agrawal et al. 2015; Bolderdijk and Steg 2015; Schwartz et al. 2015), and because pursuing small financial gains is perceived not worth the effort (Bolderdijk et al. 2013; Dogan et al. 2014).

Providing information on the causes and consequences of climate change or on effective mitigation actions increases people's knowledge and awareness, but is generally not effective in promoting mitigation actions by individuals (Abrahamse et al. 2005) or organisations (Anderson and Newell 2004). Fear-inducing representations of climate change may even inhibit action when they make people feel helpless (O´Neill and Nicholson-Cole 2009). Yet, energy-related recommendations and feedback can promote energy savings, load shifting in electricity use and sustainable travel, particularly when framed in terms of losses rather than gains (Gonzales et al. 1988; Wolak 2011; Bradley et al. 2016; Bager and Mundaca 2017). Also, credible and targeted information at the point of decision can promote mitigation action (Stern et al. 2016). Information is more likely to promote mitigation action when it is delivered by a trusted source, such as peers (Palm 2017), advocacy groups (Schelly 2014), and community organisations (Noll et al. 2014). Also, information is more effective when tailored to the personal situation of actors, and when resonating with actors' core values (Abrahamse et al. 2007; Boomsma and Steg 2014; van den Broek et al. 2017; Daamen et al. 2001; Wolsko et al. 2016; Bolderdijk et al. 2013a). This explains why home energy audits promoted energy savings (Delmas et al. 2013; Alberini and Towe 2015), and investments in resource efficiency in buildings and renewable energy generation (Kastner and Stern 2015).

Energy use feedback generally promotes energy saving behavior within households (Grønhøj and Thøgersen 2011; Fischer 2008; Karlin et al. 2015; Delmas et al. 2013; Zangheri et al. 2019) and at work (Young et al. 2015), particularly when provided in real-time or immediately after the action so that people learn the impact of different actions (Faruqui et al. 2009; Delmas et al. 2013; Stern et al. 2016; Abrahamse et al. 2005; Tiefenbeck et al. 2016). Energy labels (Banerjee and Solomon 2003; Stadelmann 2017), visualisation techniques (Pahl et al. 2016), and ambient persuasive technology (Midden and Ham 2012) can encourage energy savings as they immediately make sense and hardly require users' conscious attention. Feedback can make people aware of their previous mitigation behaviors, which can increase their environmental self-identity (Van der Werff et al. 2014), and motivate them to engage in other mitigation actions as well as to act in line with their self-image (Van der Werff et al. 2014).

Social influence approaches that communicate what other people do or think can encourage mitigation actions (Clayton et al. 2015). Indeed, social models of desired actions can encourage mitigation action (Osbaldiston and Schott 2012; Abrahamse and Steg 2013; Sussman and Gifford 2013). Informing people about their own energy use relative to others can be effective (Nolan et al. 2008; Allcott 2011;

Schultz et al. 2015), although not always, and effect sizes are relatively small (Abrahamse and Steg 2013) compared to other types of feedback (Karlin et al. 2015).

Interventions that capitalise on people's motivation to be consistent can promote mitigation actions (Steg 2016). Examples are commitment strategies where people pledge to engage in mitigation actions (Abrahamse and Steg 2013; Lokhorst et al. 2013), implementation intentions where they additionally explicate how and when they will perform the relevant action and how they would cope with possible barriers (Bamberg 2000) (Bamberg 2002), and hypocrisy-related strategies that make people aware of inconsistencies between their attitudes and behavior (Osbaldiston and Schott 2012).

Bottom-up approaches can promote mitigation behavior (Abrahamse and Steg 2013). Indeed, community energy initiatives can encourage low carbon behavior among their members (Middlemiss 2011; Seyfang and Haxeltine 2012; Abrahamse and Steg 2013; Sloot et al. 2018). Organisations can promote mitigation behavior among their employees by communication their mission and strategies to mitigate climate change (Ruepert et al. 2017).

Default options, where a preset choice is implemented if users do not select another option offered, can promote mitigation actions such as energy savings, green electricity uptake, and meat-free meals options (Pichert and Katsikopoulos 2008; Ölander and Thøgersen 2014; Kunreuther and Weber 2014; Bessette et al. 2014; Ebeling and Lotz 2015; Liebe et al. 2018; Campbell-Arvai et al. 2014).

6.7.6.2 Acceptability of policy, mitigation options and system changes

Public acceptability reflects the extent to which the public evaluates climate policy, mitigation options, and system changes in a favorable or unfavorable way, which can shape, enable, or prevent the transition to net-zero energy systems. Public acceptability of climate policy and mitigation options is higher when people expect more positive and less negative consequences of it for self, others, and the environment (Demski et al. 2015; Drews and Van den Bergh 2016; Perlaviciute and Steg 2014). Public opposition may result from a culturally valued landscape being affected by renewable energy development (Warren et al. 2005; Devine-Wright and Howes 2010), particularly when these threaten place-based identities (Devine-Wright 2009; Devine-Wright 2013; Boudet 2019). Acceptability can increase when people experience positive effects after a policy or change has been implemented and consequences appear to be more positive than expected (Schuitema et al. 2010; Eliasson 2014; Weber 2015); effective policy trials can thus build public support for climate policy.

Next, climate policy and low carbon options are evaluated as more fair and acceptable when costs and benefits are distributed equally, and when nature, the environment and future generations are protected (Schuitema et al. 2011; Drews and Van den Bergh 2016). Compensating affected groups for losses due to policy or systems changes enhanced public acceptability in some cases (Perlaviciute and Steg 2014), but people may disagree on which compensation would be worthwhile (Aitken 2010; Cass et al. 2010), or feel they are being bribed (Cass et al. 2010; Perlaviciute and Steg 2014). Earmarking revenues of pricing policy for environmental purposes (Steg et al. 2006; Sælen and Kallbekken 2011; or redistributing revenues towards those affected (Schuitema and Steg 2008); is most likely to enhance acceptability of such policies.

Further, climate policy and mitigation options, such as renewable energy projects, are perceived as more fair and acceptable when the public (Dietz 2013; Bernauer et al. 2016; Bidwell 2014) or public society organisations (Bernauer et al. 2016; Terwel et al. 2010) could participate in the decision making. People want to be informed and able to participate in decision making on climate policy and mitigation options (Devine-Wright 2005; Terwel et al. 2012; Perlaviciute and Squintani 2020; Arvai 2003; Walker et al. 2017). People particularly want to participate in decision making on local projects, and less in setting national or general policy goals (Perlaviciute and Squintani 2020). Public acceptability is particularly higher when people can influence major rather than only minor decisions (Liu et al. 2019a). Public participation can enhance the quality and legitimacy of decisions by including local knowledge and views that may otherwise be missed (Bidwell 2016; Dietz 2013).

Public support is higher when people trust responsible parties (Perlaviciute and Steg 2014; Jiang et al. 2018; Drews and Van den Bergh 2016; Liu et al. 2019; Michaels and Parag 2016). Public support for unilateral climate policy is rather strong and robust (Bernauer et al. 2016a), and not lower than support for multilateral policy (Bernauer and Gampfer 2015).

Public acceptability of climate policy and low carbon options differs across individuals. Climate policy and low carbon options are more acceptable when people strongly value other people and the environment, and support egalitarian worldviews, left-wing or green political ideologies, while acceptability is lower when people strongly endorse self-centered values, and support individualistic worldviews (Dietz et al. 2007) (Perlaviciute and Steg 2014) (Drews and Van den Bergh 2016). Similarly, public decision makers support climate policy more when they endorse environmental values (Nilsson et al. 2016). Climate and energy policy is more acceptable when they are concerned about climate change (Hornsey et al. 2016), and when they believe their actions would help mitigating climate change, and feel responsible to mitigate climate change (Steg 2005; Jakovcevic and Steg 2013; Ünal et al. 2019; Eriksson et al. 2006; Drews and Van den Bergh 2016; Kim and Shin 2017).

6.7.7 The Costs and Benefits of Energy System Transitions in the Context of Sustainable Development

The attractiveness of energy sector mitigation actions ultimately depends on the way that they provide benefits and reduce the costs for the many different priorities that societies value. While costs and benefits of climate mitigation are often considered in the context of pure economic outcomes – GDP losses, changes in value of consumption – costs and benefits should be viewed with a broader lens. Indeed, it is important to see climate mitigation not as a separate from countries' broader growth and development strategies, but rather as a key element of those strategies.

Cost reductions in key technologies – notably solar PV, wind and batteries – have driven down expectations for near-term mitigation costs; mitigation may well be negative or zero cost in some circumstances (*high confidence*). Past assessments have quantified the costs for climate change mitigation using different metrics, i.e. (implied) carbon prices, GDP losses, investments towards energy infrastructure and energy system cost in low carbon scenarios. For the energy sector, there is a wide range of assessments on (regional) mitigation costs based on integrated assessment and energy system models. For example, scenarios include (implied) carbon prices in 2030 of less than USD 20/t-CO_2, but also more than USD 400/t-CO_2 depending on the region, sector boundary and methodology (model specifications plus scenarios) applied (e.g. Bauer et al. 2016; Brouwer et al. 2016; Oshiro et al. 2017) Vaillancourt et al. 2017; Chen et al. 2019). Those arise both from methods (Guivarch and Rogelj 2017) and uncertainties in key factors that drive costs (Meyer and Löschel 2020).

Recent developments, however, raise the prospect that costs could be substantially lower than prior estimates, particularly if key technologies continue to improve rapidly. In some regions and circumstances, short term mitigation (in particular in the electricity sector) may well come at negative cost (e.g. Brown et al. 2017; Kumar et al. 2020). Given the importance of electricity decarbonisation in near-term mitigation strategies (see Section 6.7.1), decreasing costs of solar, PV, and batteries to support their integration, have an outsised influence on near-term mitigation costs. At the same time, mitigation costs may vary across regions depending – among other things – on the characteristics of the prevalent energy systems and associated balancing needs and integration costs of renewables. The extent of existing infrastructure influences economic cost as designing new infrastructure compatible with specific climate targets is less costly as retrofitting existing high-carbon infrastructure and associated stranded assets (OECD 2015; Vinciguerra and Frenken 2015).

Long term mitigation costs are not well understood and depend on policy design and implementation, future costs and availability of technologies in hard-to-decarbonise sectors (e.g., process heat, long-distance transport), and the development of electrification processes in end-use sectors (*high confidence*). The overall cost is likely to be moderate in many circumstances (*medium confidence*). For the whole economy, scenarios in SR1.5 estimated the range of mitigation costs to be between USD 45–1050/t-CO_2 in 2050 under a higher-2°C pathway and range from USD 245–14300/tCO_2 for a below-1.5°C pathway in 2050 (IPCC 2018). For energy sectors in various regions and globally, different scenarios show a wide range of implied carbon prices in 2050, such as lower than USD 50/t-CO_2 or more than USD 900/t-CO_2 (Brouwer et al. 2016a; Rogelj et al. 2018c).

Estimates of long run mitigation costs are highly uncertain and dependent on various factors. For example, faster technological improvements will reduce costs and drive additional deployment, as has recently been the case for PV. International cooperation in climate mitigation reduces total economic mitigation costs and corresponding prices of carbon (Paroussos et al. 2019). Earlier action on mitigation helps avoid higher climate damages in the future, thus improving the confidence of carbon prices towards the lower bounds of the wide ranges presented above (Kaufman et al. 2020; Sanderson and O'Neill 2020). Accordingly, while the policy losses for adhering to 2°C targets were 3-11% in AR5, the median in newer studies is 3% (Gambhir et al. 2019; Su et al. 2018). Longer-term mitigation costs are also projected to be higher because earlier, low-cost opportunities get utilised first and efforts after that would require mitigation in hard-to-decarbonise sectors (Section 6.6). It is important to note that the benefits of mitigation are significant with most countries noticing a gain in GDP in a world with 1.5°C instead of a 2°C warming (Burke et al. 2018; Pretis et al. 2018).

Furthermore, focusing only on the technological costs of mitigation may lead to neglect other important aspects, such as distributional aspects or on other benefits of mitigation in the context of sustainable development goals. For example, cumulative mitigation costs are comparably high for developing countries. These costs are estimated to amount up to 2-3% of GDP, which indicates difficulties for mitigation without adequate support from developed countries (Fujimori et al. 2020; Dorband et al. 2019). In scenarios involving large amounts of stranded assets, the overall costs of transitions also include the additional costs of early retirements (Box 6.11).

Strategies to increase energy efficiency and energy conservation are, in most instances, mutually reinforcing with strategies to support sustainable development. Improving efficiency and energy conservation will promote sustainable consumption and production of energy and associated materials (SDG-12) (*high confidence*). Contrastingly, successful implementation of demand-side options requires sustainable partnerships (SDG-17) between different actors in energy systems i.e. governments, utilities, distributors and consumers (*high confidence*). Many authors have argued that energy efficiency has a large untapped potential in both supply and demand (Lovins 2018; Méjean et al. 2019). For example, improved fossil power plant efficiency could lower the costs of CCS from USD 80-100/t-CO_2 for a subcritical plant to <USD 40/t-CO_2 for a high efficiency plant (Hu and Zhai 2017; Singh et al. 2017). This could reduce the key tradeoff of SDGs with CCUS i.e. increased unaffordability of power access. Eliminating electricity transmission losses in has been estimated to be able to mitigate 500 Mt-CO_2/year globally (Surana and Jordaan 2019). For several other options, such as methane mitigation from the natural gas sector, the costs of infrastructure refurbishing could be recovered with the value of additional resource thus generated (Kang et al. 2019). These options pertaining to transmission of heat and electricity would directly benefit from SDG-9 on infrastructure improvement targeted by several governments.

The majority of efficiency improvement avenues, nevertheless, are present on the demand-side (Chapters 5, 7-12). Efficient technologies in the building, industry and transport are particularly cost-effective in developing countries where new infrastructure is rapidly getting built with an opportunity to create positive path dependencies (Section 6.7.3; Nabernegg et al. 2017; Yu et al. 2017). Aside from reducing energy consumption, such measures also reduce the need for resource extraction (e.g. fossil fuels or metal mining in case of renewables) (Luderer et al. 2019). This is an important precursor to SDG-12 on sustainable consumption and production of minerals. Moreover, these approaches reduce the need for – and therefore SDG tradeoffs associated with – CDR towards the end of the century (covered later in this section) and avoid temperature overshoot (van Vuuren et al. 2018). But fully leveraging the demand-side efficiency would entail behavioral changes and thus rely on strong partnerships with communities (SDG-17). For instance, approaches that inform households of the economic value of conservation strategies at home could be particularly useful (Niamir et al. 2018). An important distinction here between SDGs focusing on infrastructural and behavioral interventions is the temporal contexts. Improving building heat systems or a grid with reduced T&D losses would provide climate mitigation with one-time investments and minor maintenance over decades. On the other hand, behavioral changes would be an ongoing process involving sustained, long-term interactions with societies.

An increase in electrification via low-carbon energy will support and reduce the costs of key elements of human development (education, health, employment) (*high confidence*). Greater access to electricity might offer greater access to irrigation opportunities for agricultural communities (Peters and Sievert 2016; Peters and Sievert 2016) which could have the potential increasing farmer incomes again aiding SDG-1. Coordinated electrification policies also improve enrollment for all forms of education (Kumar and Rauniyar 2018; López-González et al. 2020). Empirical evidence from India suggests that electrification reduced the time for biomass collection thus improving time for schooling for children – SDG-4/5 (Khandker et al. 2014). Similarly, reduced kerosene use has been targeted by developing countries' government, that has been associated with improved indoor air quality – SDG-3 (Barron and Torero 2017; (Lewis and Severnini 2020). These indicate positive linkages for climate change mitigation with other goals, that improve the favorability of solar PV among the public and policy makers. Indeed, the "goodwill" towards solar PV is the highest among all the major mitigation options considered in this chapter (Section 6.4.2).

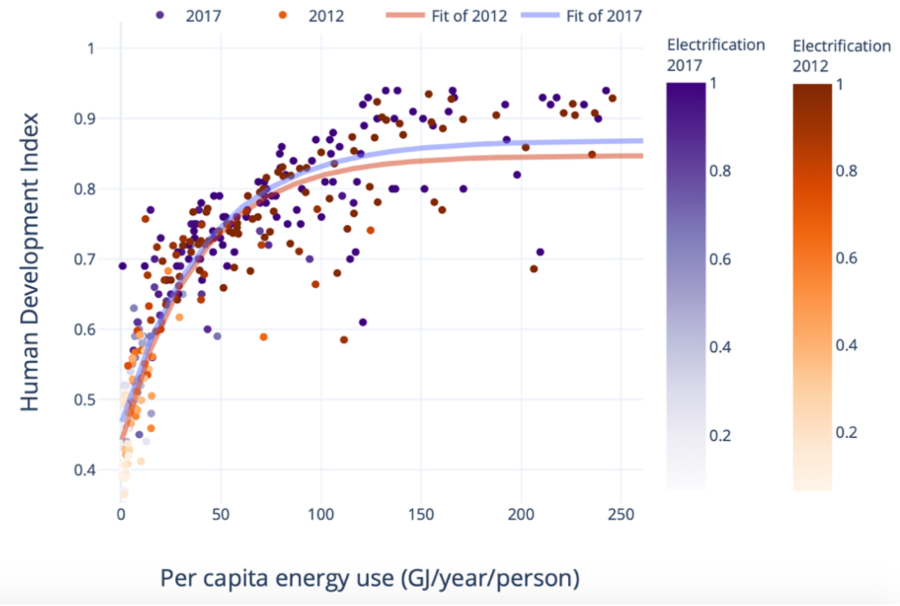


Figure 6.36 The relationship between total per capita energy use, rate of electrification and human development index. Improved efficiency has lowered the energy demand required for meeting a threshold HDI during 2012-2017

Another key aspect in this interface of electrification and sustainable development is the impact of energy efficiency. Improved energy efficiency is interlinked with higher economic growth in Africa

(Ohene-Asare et al. 2020; Lin and Abudu 2020). In several cases, electrification has directly provided higher energy efficiency as well as a pathway to achieving other SDGs. For instance, availability of electrified cooking heat reduces primary energy requirement considerably compared to traditional stoves (Batchelor et al. 2019) (Yang and Yang 2018) while also promoting improved indoor air quality (SDG-3). Similarly, developing countries may note significant energy conservation through PV-powered irrigation and water pumping post-electrification, which has the added advantage of promoting SDG-6 on clean water (Elkadeem et al. 2019; Rathore et al. 2018). Past trends have also indicated that in some Asian countries, electrification has been obtained at lower income levels as compared to developed countries (Rao and Pachauri 2017). Indeed, these transformations have had positive impacts. For instance, based on existing evidence, human development index (HDI) greater than 0.7 (Figure 6.36) which signifies high development is now possible at close to 30 GJ/year/person. This was attainable at much higher energy consumption of 50 GJ/year/person in the first decade of this century. Improved efficiency follows as a function of electrification and accordingly, leads to improved quality of life.

Climate mitigation actions, phasing out fossil fuels in favor of renewables, is likely to have considerable positive SDG benefits. However, it is essential to plan transitions such that tradeoffs such as unemployment to fossil fuel workers are minimised (*high confidence*). Consider, for example, the case of coal phaseout discussed in Box 6.2 and Section 6.3.4. While it is an important part of SDGs 3, 7 and 14, it is also anticipated to create large job losses if not properly managed. That said, there are large potential employment opportunities that may be created in alternative sectors such as renewables and bioenergy for both skilled and unskilled workers. “Sustainable transition” pathways have indicated a complete fossil phaseout which could entail numerous other co-benefits. For instance, fossil fuels are estimated to generate only 2.65 jobs per USD 1M as compared to projected 7.49 from renewables (Garrett-Peltier 2017). Moreover, future energy sector jobs may be in tandem with bioenergy agriculture since It has been estimated that BECCS can reduce loss of coal employment while also creating 22,000 new jobs by the midcentury in the US itself (Patrizio et al. 2018; Tvinnereim and Ivarsflaten 2016) Phasing out of fossil fuels would also lead to a key evolution in SDG-3 via air quality improvements, by reducing PM2.5 emissions, thereby reducing premature deaths (notably in China:(Li et al. 2020b; He et al. 2020). Consequential energy transitions from fossil fuels to renewables, as well as within fossil fuels (coal to gas switching) are already being observed in some regions, spurred by climate concerns (EU, India), health concerns (China), market dynamics (US), or consumer choice (for example in the transport sector). Our synthesis of the energy systems literature points out, analogous to (McCollum et al. 2018c), that the scope for positive interactions of energy systems with SDGs is considerably larger than the tradeoffs (Figure 6.36).

Figure 6.37 Nature of the interactions between SDG7 (Energy) and the non-energy SDGs (McCollum et al, 2018). Reproduced under Creative Commons 3.0 License.

CDR and CCUS often create large land and water tradeoffs with SDGs, compared to renewables. Large-scale CDR and CCUS therefore requires understanding appropriate geographical context to reduce implications on water and food systems (*high confidence*). The water impacts of CO_2 capture are very large and could create plant shutdowns (Realmonte et al. 2019; Liu et al. 2019). Additionally, Similarly, high-salinity brines are also produced from geologic carbon sequestration – which is common to several technologies, whether fossil fuel CCS, BECCS or direct air capture (Arena et al. 2017; Klapperich et al. 2014). Both these implications of CCUS/CDRs are closely related to SDG-6 on clean water. As discussed in Sections 6.6 and 6.4.2.6, a majority of the CDR discussion in energy systems pertains to BECCS which could affect food prices based on decision choices on crop pricing, marginal land utilisation etc. (Daioglou et al. 2020a). Several CDR processes also require considerable infrastructure refurbishment and electrification to reduce upstream CO_2 emissions (Singh and Colosi, 2021). This could influence SDG-2 on zero hunger by affecting the supply of food crops as well as creating farm employment. At the same time, large-scale CDR could also open up the potential for low-carbon transport and urban energy use that would create synergies with SDG-11 (sustainable cities and communities). Siting of such infrastructure therefore requires an understanding of the extent to which these environmental impacts trade off with climate change mitigation.

System integration would help harmonise energy-SDG synergies while eliminating key tradeoffs associated with complementary mitigation options (*high confidence*). System integration strategies focus on codependence of individual technologies in ways that optimise system performance. Accordingly, they have scope for reducing economic costs as well as SDG burdens. For instance, a major issue with solar PV is intermittency while that for green hydrogen is high costs of power required for electrolysis (both relevant directly to SDG-7 on affordable and reliable energy access). In some circumstances, the excess solar generation during daytime could be rerouted for hydrogen production ensuring higher grid stability as well as low cost of hydrogen fuel (Tarroja et al. 2015)(. Sections 6.4 and 6.6 have provided key insights into how access to low-cost hydrogen fuel would transform the public transport and promote sustainable urban transport (key thrust of SDG-11). Due to the varying patterns of solar and wind, they could also be operated in tandem, thus reducing the high material burdens associated with storage thus promoting SDG-12 on sustainable production (Wang et al. 2019d; Weitemeyer et al. 2015). For CCUS facilities, co-firing of fossil fuels and biomass could present a more gradual transition forward in terms of deep decarbonisation (Lu et al. 2019) This would avoid cost burdens due to early retirement (mitigation tradeoff associated with SDG-1) while also providing air pollution reduction (fossil fuel tradeoff associated with SDG-3) in the short-term.

Frequently Asked Questions

FAQ 6.1. Will net zero energy systems be different than energy systems today?

Net-zero energy systems will be similar to those of today in the sense that they will provide many of the same services that they provide today – for example, heating and cooling homes, allowing us to travel to work or on vacation, and powering manufacturing. But future energy systems may be different in the sense that we may also demand new services, just as we now use energy for many information technology uses that we did not anticipate 50 years ago. More importantly, net-zero energy systems will be different in the way that we produce, transform, and use energy to provide these services. In the future, almost all electricity will be produced from sources that don't emit CO_2, such as solar power, wind power, nuclear power, bioenergy, or hydropower; we will use electricity, hydrogen, and bioenergy in many situations where we use fossil fuels today; and energy will be used more efficiently than to today, for example, through more efficient cars, trucks, and appliances, buildings that use very little energy, and greater use of public transportation. Fundamental to all of these changes is that net-zero energy systems will use little or no fossil fuels.

FAQ 6.2. Can we power future energy systems on renewable energy alone?

Renewable energy technologies harness energy from natural sources that are continually replenished, for example, from the sun (solar energy), the wind (wind energy), plants (bioenergy), rainfall (hydropower), or even ocean waves (wave energy). The energy from these sources exceeds the world's current and future energy needs many times. But that does not mean that they will provide all energy in future net-zero energy systems. Only some of the energy from renewable sources can be captured at reasonable costs; other low- or zero-emissions options, such as nuclear power or fossil energy with carbon dioxide capture and storage (CCUS), may be more viable in some circumstances. Some countries have a lot of renewable energy, whereas others do not. Important sources such as solar energy, wind energy, and hydropower are all "intermittent", meaning that they cannot provide energy at all times. Many sources may also have other consequences, for example producing bioenergy may reduce biodiversity and increase food prices. For all of these reasons, it is unlikely that most future energy systems will rely entirely on renewable energy sources. But research is increasingly indicating that it will be viable, in many circumstances, to produce most or all electricity from renewable energy.

FAQ 6.3. What are the most important steps to decarbonise the energy system?

To reduce energy system emissions to zero, they must be eliminated across all parts of the system, and not just one or two. This means eliminating emissions when we produce electricity, drive our cars, haul freight, heat and cool buildings, power our data centers, and manufacture goods. Technologies need to be developed and deployed, and policies and regulations need to be put in place across the energy system. At the same time, some actions and parts of the energy system provide greater near-term opportunities to reduce emissions than others, even if a comprehensive approach is critical to get on a path to net-zero emissions. Key near term actions include deploying low- and zero-carbon electricity sources; halting the construction of new coal-fired power plants and retiring existing coal-fired power plants; limiting the construction of new gas-fired power plants; installing electric heaters ("heat pumps") in homes and businesses; replacing cars using gasoline with those using electricity; and installing more efficient technologies wherever possible. These should be accompanied by efforts to improve and test out options that will be important later on, including hydrogen or biofuels in cars and trucks, and fossil power plants, bioenergy power plants or refineries with CCUS.

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