Chapter 6: Energy Systems

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Executive Summary

Energy systems will need to become "carbon-neutral" by 2050 or within several decades after 2050 to meet the Paris goals. The energy system is the largest single contributor to anthropogenic emissions. The Paris goals cannot be met without largely eliminating energy system emissions. Energy systems will need to become carbon-neutral around 2045-2060 to limit temperature change to 1.5°C; they will need to become carbon-neutral around 2060-2075 to limit temperature change to 2.0°C (assuming no CDR outside of the energy system). Reaching zero CO_2 by 2050 would require emissions to decrease by about 3.3%/year for the next 30 years, as compared to average growth of over 2%/year from 2000 to 2018.

Energy system CO_2 emissions continue to increase. This is the opposite of what needs to happen to meet the Paris goals. Emissions from fossil fuel combustion and industrial processes were roughly flat in 2015, but have rose by 1.1 %/year from 2015 to 2018. Fossil fuel use rose 0.6%/yr between 2015 and 2017.

Recent years have seen rapid improvements in several energy system mitigation options, including PV cells and batteries. Investment costs for distributed PV have dropped by 60-80% during 2010-2018. Battery costs have dropped by more than half between 2015 and 2018. These changes have spurred rapid changes in electricity generation and electric transportation. Renewable generation is now cheaper than fossil generation in many regions, and projections indicate that light-duty electric vehicles may be competitive with internal combustion engines in a matter of years (see Chapter 10).

Electricity generation from low-carbon sources, particularly wind and solar power, has increased substantially in recent years. While substantial, this growth is well below what would be needed to meet the Paris goals. Policy, societal pressure to limit fossil generation and associated pollution, and technological improvements, particularly in PVs and wind power, have all driven renewable electricity deployments**.** From 2013 to 2017, generation from low-carbon electricity has increased by 23%. The vast majority of the growth has been solar PV and wind power, which have grown by 217% and 74%. Growth in hydropower (7%), nuclear power (6%), and CCUS has been limited. Studies indicate that generation from low-carbon sources will need to grow to more than 80% over the next 30 years to limit temperature change to 2°C.

Although there is no single "best" future carbon-neutral energy system, there are several robust characteristics that are valuable for guiding strategy. There is a robust literature on scenarios that includes integrated assessment modelling scenarios, national long-term strategies, and official mid-century strategies. All of these scenarios provide characterizations of future carbon-neutral or, at least, low-carbon energy systems. Several key characteristics of carbon-neutral energy systems emerge from this literature. This includes: (1) electricity systems that produce zero CO_2 or that remove CO_2 from the atmosphere; (2) widespread electrification of end uses, particularly in areas such as space heating, cooking, and light-duty transport; (3) substantially lower use of fossil fuels than today, particularly without CCUS, (4) targeted use of alternative fuels (e.g., hydrogen, bioenergy, ammonia) to substitute for fossil fuels in harder to decarbonize sectors; (5) more efficient use of energy than today; (6) greater integration across components of the energy system; and (7) use of some level of carbon-dioxide removal.

The global energy system has to be fundamentally transformed over the coming decades to meet the Paris goals. Past IPCC assessments have continually emphasized the scale and pace of the energy-system transformation needed to meet the Paris goals. The necessary pace and associated challenges have only increased since AR5 as emissions have continued to rise and there has been increasing emphasis on limiting temperature change to 1.5°C.

There are many technology options available today for taking the first steps to reduce energy system emissions consistent with the Paris goals. Major technological challenges will not emerge until well past 2030. Energy supply options include solar power, wind power, nuclear power, geothermal power, biopower, fossil or biopower with CCS. Some of these are in widespread use today, whereas others such as CCUS are technological viable but have seen only limited use. Energy storage is increasingly viable for use in electricity grids. Grid management techniques and technologies are rapidly evolving. A wide variety of technology options are available to switch to low-carbon fuels and constrain energy demand growth (see chapters 8 through 11).

Climate change may have important implications for the energy system, particularly in countries reliant on hydropower and bioenergy. While there is substantial uncertainty about the exact nature of the changes, research is increasingly demonstrating that climate will have an important influence on the 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.

The challenges of energy system transformation go well beyond technology, particularly in the near-term. The energy system is a web of interacting technologies and infrastructure, institutions, firms, and individuals**.** The large-scale technological transformations needed to reduce energy system emissions to zero will not occur without important changes in all of these interacting systems. This implies that societal and institutional changes are fundamental to energy system transformation. These broader challenges are currently at least as important as the technological challenges.

The viable speed and scope of energy system change will depend how well such change can support broader societal objectives and garner broader societal support. The energy system is fundamental to many of the most basic goals of human societies. Energy systems are linked to air and water pollution, energy security, food security, economic prosperity and international competitiveness, employment, and provision of the basic services (such as heating, cooling, lighting, cooking) that access to energy provides. Energy system transformation will not occur if it is in conflict with these goals. Air pollution has been a major driver of recent energy system mitigation in some countries.

Energy system mitigation will create opportunities for some industries and associated groups while negatively impacting some industries and groups, particularly in the near-term. Most fundamentally, meeting the Paris goals will decrease the use and value of fossil fuels, affecting those industries, individuals, and societies that dependent on fossil revenues and fossil-related jobs. Fossil resources left in the ground will be substantially less valuable. In contrast, emerging industries, such as renewable energy industries or non-fossil transportation are set to grow substantially. Investments in low-carbon electricity generation, for example, could be around $700 billion per year by 2030, as comparison to overall electricity generation investment today of $350 billion.

Every country will need to chart a course toward carbon-neutral energy systems that meets its own needs and national circumstances. While many studies have identified “economically optimal” energy systems, countries will make choices on how to navigate an energy system transition based on a wide variety of factors. These include national resource bases, energy security, energy access, public perceptions about particular technology options, air pollution, water and energy interactions, and many more.

If current 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 or buildings can last for decades or even centuries. 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 will substantially increase the challenge of meeting the Paris goals.

Many new investments in fossil infrastructure are at risk of being “stranded” -- retired early – in order to meet the Paris goals. New investments in fossil generation, particularly coal generation, without CCUS are inconsistent with the Paris goals. While natural gas generation provides near-term reductions relative to coal-fired generation, it too creates emissions and must be retired if energy-sector emissions are to be brought to zero. Investments in refining may be stranded with a move to electric transportation infrastructure.

6.1 Introduction

The energy system is the main contributor to climate change. Reducing energy sector emissions is therefore the most critical imperative for climate mitigation. This and the other chapters in this assessment explore options and challenges to energy sector mitigation from multiple viewpoints and to varying degrees. Each chapter explores specific issues, but all are related in the common theme of reducing anthropogenic emissions, and energy sector mitigation is a foundational theme throughout the assessment.

Within the broader context of this overall assessment, this chapter focuses on two aspects of the energy system mitigation puzzle. First, it takes a holistic view of the energy system, including the integration of end uses with energy supply, transformation, and transportation (that is, transportation of energy). As energy systems become increasingly integrated and interconnected, a system-wide perspective is necessary for understanding mitigation opportunities and challenges. While specific end use mitigation options are discussed in other chapters, this chapter discusses the integration of end use mitigation into an overall energy system perspective. Second, this chapter assesses specific mitigation options in energy supply, transformation, and transportation. 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), and industry (Chapter 11).

The chapter is motivated by the following key questions, each of which is addressed in a separate section. First, what is an energy system (Section 6.2)? A common perspective is that energy systems are a collection of physical technologies that interact with one another. While this is true, energy systems are also embedded in broader social and institutional systems. Interactions with these broader systems in many ways define how energy systems have evolved and might evolve in the future. Second, what are recent trends in the energy system that might influence its future evolution and options for reducing emissions (Section 6.3)? Recent trends provide both opportunities and obstacles to energy system decarbonisation. Third, what is the status and potential of energy supply, transformation, energy transportation, and system-wide mitigation options (Section 6.4)? The assessment of mitigation options in this chapter stops short of assessing end-use sector options, as these are taken up in other chapters of this assessment. Fourth, how will climate change itself affect the energy system and alter the potential energy system mitigation options (Section 6.5)? The climate is changing and will continue to change. Many energy system mitigation options may be vulnerable to, or even potentially advantaged by, climate change. An understanding of how climate might affect the energy systems is therefore critical for long-term mitigation planning. Fifth, what are the key characteristics of “climate-neutral” energy systems – those that emit no CO_2 or that actually sequester CO_2 from the atmosphere (Section 6.6)? To limit temperature change, energy system emissions must ultimately be brought to or near zero. Climate-neutral energy systems are a way-point on longer-term mitigation pathways and provide important strategic context for actions taken today. Sixth, and finally, what are the transition pathways toward and through climate-neutral energy systems (Section 6.7)? To reach particular temperature levels, such as 2°C or 1.5°C, what is the pace of investments needed, how quickly must emissions be reduced, when must the energy system reach carbon-neutrality, and how can investments and other actions taken today best support the transformation and not put in place barriers to deep decarbonisation?

Several cross-cutting themes run throughout this and the other chapters of this assessment. One theme is the feasibility and desirability of different energy system transitions. Among the most important questions that policy makers and other decision makers frequently ask is which pathways are most viable for limiting temperature change to particular levels, such as 2°C or 1.5°C. Still others ask whether particular pathways or long-term temperature goals are even feasible. While this chapter does not provide definitive answers regarding feasibility, it does provide insights into the characteristics of different energy system transformation pathways that might inform assessments of what may or may not be feasible or desirable.

A second theme is the representation of the costs and benefits of energy system mitigation options. Aggregate economic cost measures such as GDP impacts are one useful indicator of the overall societal implications of energy system transformations. They are, however, far from comprehensive and can provide misleading guidance if assessed in isolation. The societal value of any energy system transformation must be assessed against a much broader set of societal goals from clean air and water to energy access to poverty alleviation to energy and food security. For the purposes of this chapter, this broader framing of costs and benefits is defined in terms of interactions with sustainable development goals. The linkage to sustainable development is interwoven with questions of feasibility and desirability. The feasibility and desirability of any pathways is dependent on the associated costs and the degree to which that pathway can support multiple societal objectives and not just those associated with climate mitigation.

The third theme is that of regional barriers and opportunities. Across the world, energy systems can vary dramatically based on all manner of different influences, including energy resource endowments, interlinkages through energy trade, societal preferences and perspectives (e.g., perspectives on nuclear power, energy access, or energy security), economic development (e.g., GDP, access to capital markets), political economy factors (e.g., powerful interest groups or the ability of institutional systems to make change), the nature of domestic industry and its associated demands, the level of urbanization and the character of the urban environment (e.g., largely suburban or more concentrated), and the local climate and its effect on heating and cooling demands. For this reason, no two countries have identical energy systems, and no two countries will follow exactly the same pathway toward deep reductions in energy sector emissions. Understanding these different influences on national energy systems and their ability to change is critical for developing sound climate mitigation strategies. Policy makers look to IPCC reports for guidance that might apply to their specific national circumstances. While this chapter does not identify pathways for specific countries, it nonetheless attempts to provide guidance that might be valuable for national decision making. Whenever possible, the chapter attempts to identify how particular national characteristics might influence mitigation options and pathways.

6.2 Elements of Energy Systems

The energy system is broad and complex. Energy systems are frequently defined in terms of the physical infrastructure that is used to extract, transform, transport, and convert energy to provide energy services. An energy system, however, extends well beyond this physical system and include the broad set of societal and institutional systems in which energy technologies are embedded. This broader view is essential for understanding energy system mitigation, as these broader societal and institutional factors have an outsized influence on energy system transformations and the potential to rapidly reduce energy system CO_2 emissions.

For our purposes of this chapter, we define an energy system to include three parts: (1) a physical energy system, (2) the institutions, laws, and regulations that govern the operation of the physical energy system, and (3) the firms, consumers, or other actors that directly interact with the energy system, making investments and using energy for a wide variety of purposes (Figure 6.1).

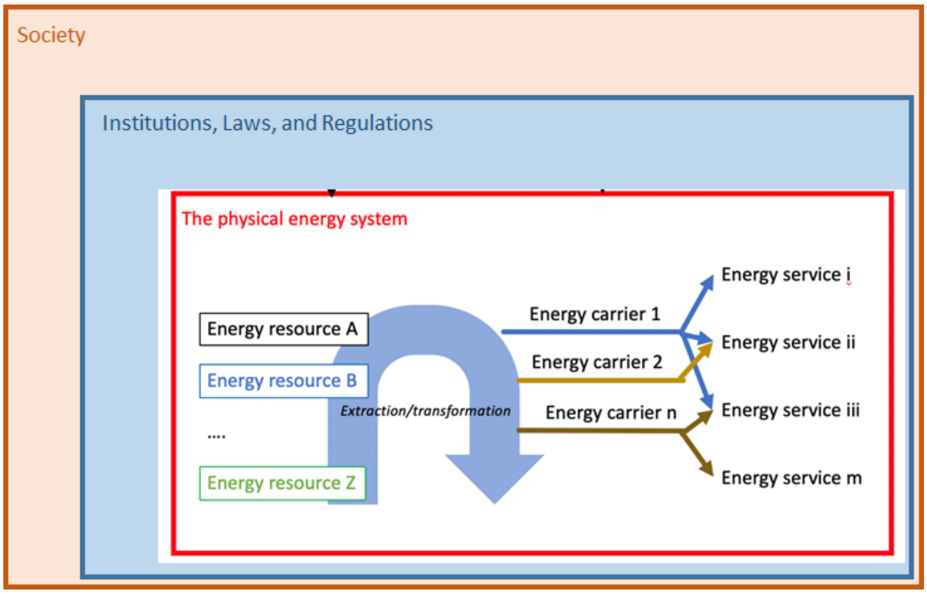


Figure 6.1 The energy system is the integration of the physical energy system, the institutional and operational systems, and broader natural and social systems [Placeholder for SOD-Draft figure – to be revised]

The evolution of the energy system is driven by the way that these various systems interact. Societal needs for basic services such as heating, cooling, lighting, transportation, and cooking, as well as for consumer products are the reason that energy is produced in the first place. Air pollution that can result from electricity production in the physical energy system interacts with public health goals and has been a major driver for energy system change. All aspects of energy systems are governed by laws, regulations, and actual institutions that reside within businesses and governments at all levels. Goals associated with energy access or energy security can have an outsized influence on countries' approaches to resource extraction, energy trade, and geopolitics. While basic economic considerations are important, understanding energy system evolution is therefore very much about understanding the way that energy system interacts with broader institutional and societal systems**.**

The **physical energy system** is often understood to follow a linear pathway from the sources of energy through the provision of energy services for firms and consumers. This linear pathway can be defined as consisting of four parts: energy resources, energy extraction and transformation, energy transport and storage, and provision of energy services. Energy sources include fossil resources, renewable resources such as solar energy, wind energy, and tidal energy, geothermal energy, bioenergy crop, and uranium for use in nuclear power. Energy extraction and transformation is the process of converting these resources into energy carriers that can be used to supply energy services. Important energy carriers include solid fuels (e.g., coal), liquid fuels (e.g., gasoline, ethanol, or jet fuel), and gaseous fuels (e.g., methane, electricity, and hydrogen). The means of extracting and transforming these resources are as varied as the sources themselves. Petroleum, for example, is first extracted from the underground and then refined into a range of different types of fuels and other products in large-scale refineries. Bioenergy crops must be grown, harvested, then converted to any range of different energy carriers from biodiesel to biogas to electricity. Solar energy can be directly converted to electricity using solar photovoltaic cells or concentrating solar power stations. There are also many means to transport energy, from electricity transmission and distribution lines to trains for carrying coal to tankers for carrying liquified natural gas. The provision of energy services is the reason why energy systems exist in the first place. 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 clean, and so forth. These services are provided by technologies from air conditioners to cookstoves, to airplanes, to electric motors.

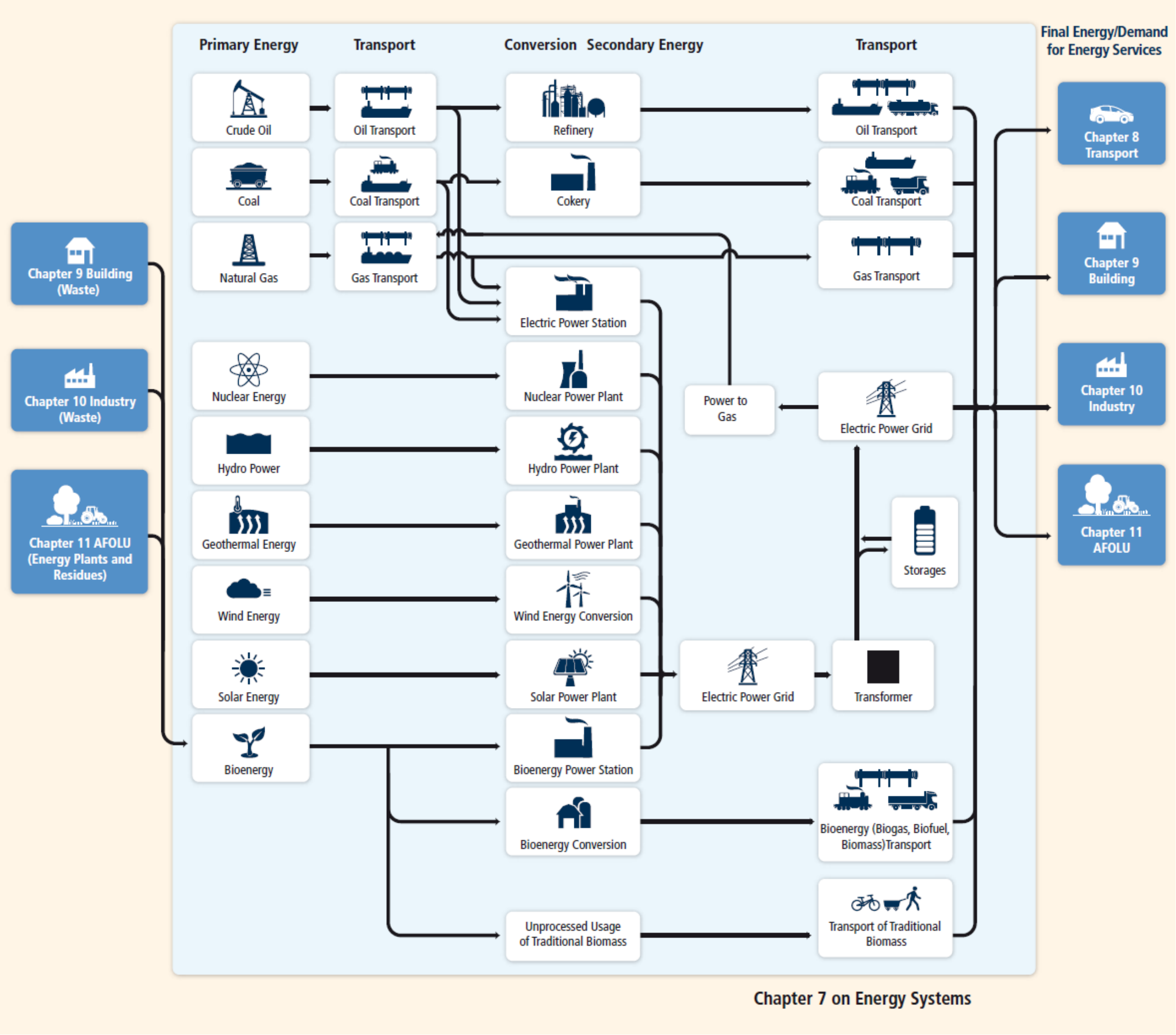


Figure 6.2 Overview of the physical energy system (Source, IPCC AR5) [Placeholder for SOD-Draft figure – to be revised]

The physical characteristics of an energy system do not define its operation. The operation of energy systems is governed by a wide range of institutions and related operating rules and regulations. These institutions, rules, and regulations are critical to the effective functioning of energy systems. Examples include rules for dispatching electricity generation technologies, water management rules that define the availability of hydropower, 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. The institutions that surround an energy system can be as important to an energy system as the physical system. Indeed, discussions of carbon-neutral energy systems often revolve around the manner in which these systems will be operated, for example, how renewable energy can be integrated in large proportions into the energy system.

The entities that constitute society more broadly – people, firms, and other actors – interact with the energy system in a variety of ways that influence how energy systems are designed and operated. Energy end users define what the energy system is meant to produce, for example, transportation, lighting, heating and cooling homes, cleaning, entertainment, or driving industrial and agricultural processes. Energy systems are ultimately constructed to serve these demands, which themselves respond to societal trends and other influences. Consumers make investments in equipment that uses energy and also invest in decentralized energy transformation (e.g., rooftop solar) and storage. Firms and governments also invest in equipment to produce, transform, and transport energy, from power plants to oil tankers. Governments provide the regulatory framework and together with firms define the rules by which energy systems operate. All energy users engage in the energy system operation by demanding energy at particular times and in particular forms. They can adjust their demands characteristics to support energy system change, for example, by using less energy or by adjusting electricity load profiles to better support particular electricity generation mixes.

The energy system interacts with society in many different ways besides directly delivering goods and services to end users, however. Energy systems have an outsized influence on a range of other societal goals, many associated with sustainable development. This includes energy access, energy security, economic activity and employment, and a broad range of environmental concerns such as nuclear waste and air pollution. These other concerns are frequently of more immediate concern than climate mitigation and can therefore drive energy system decisions. Energy system dynamics are also intimately linked to large-scale geopolitical issues associated with the ownership and extraction of resources. The success in addressing these other concerns, or the failure to take them into account, can have an outsized influence on the success or failure of climate mitigation in the energy system. They are also critical to understanding future energy system because they can define the possible pathways that countries might take to reduce emissions while simultaneously addressing concerns that may, in fact, be of greater national concern.

The vast majority of energy systems are connected to one another across a range of different scales. Cities sit within regional or national electricity grids. They obtain gasoline from refineries often some distance away. Electricity grids can cross national borders. Natural gas, oil, and coal are all transported long distances across national borders on land and over water. These linkages imply that energy system change in one country or locale will influence and be influenced by those in other countries or locales. While overall economic advantages can accrue from greater integration, integration can also reflect upon other societal motivations that drive energy system change.

Taking these pieces together, an energy system is more than the sum of the components. The manner in which the different components interact with one another defines its evolution and the opportunities and barriers to mitigation.

6.3 Recent Energy System Trends and Developments

The purpose of this section is to identify recent trends and drivers that will influence energy system evolution and the potential for mitigation. The motivating questions for the section are as follows. (1) What are the key trends in energy system development? (2) How might they influence future energy system evolution? The section focuses on a set of recent energy system trends and developments that are particularly relevant for reducing emissions. The focus in this section is on developments relevant to energy supply and the energy system as a whole. Developments specific to demand sector are considered in other chapters of this report.

6.3.1 Energy sector emissions continue to grow

Current trends in energy system emissions, if continued, will not limit global temperature change to “well below 2°C”. Fossil fuel emissions will need to decline rapidly to limit temperature consistent with the Paris goals (see Section 6.7). In contrast, energy sector emissions have increased at a rate of 1 % annually over the last five years (2014-2018). Fossil fuel CO_2 emissions reached 37.8 Gt/yr in 2018 and accounted for approximately two-thirds of the annual global anthropogenic GHG emissions at that time. Global fossil fuel CO_2 emissions increased by 2.6% per year from 2000 to 2014, remained almost flat in 2015, and then began rising again, growing by 1.1 % per year from 2015 to 2018 (see Figure 6.) (Crippa et al. 2019). The increase has been driven in large part 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. Coal was the single largest contributor the growth in emissions between 2017 and 2018. Emissions from coal generation exceeded 10 $GtCO_2$ in 2018 (IEA 2018a), increasing by 2.9% from 2017 to 2018 (Figure 6.).

Table 6.1 Fossil fuel, industrial processes and product use CO_2 emissions. (Crippa et al. 2019)

Year	$GtCO_2$/yr	tCO_2/cap/yr	tCO_2/kUSD/yr	Population (Billion)
1990	22.7	4.3	0.48	5.3
2005	30.0	4.6	0.39	6.5
2017	37.1	4.9	0.32	7.5

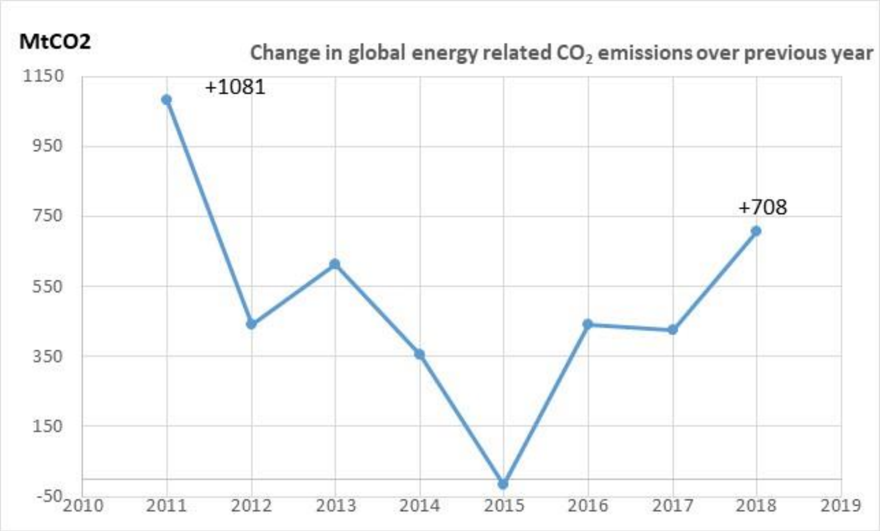


Figure 6.3 Change in global fossil fuels CO_2 emissions over previous year (Source: Crippa et al., 2019).

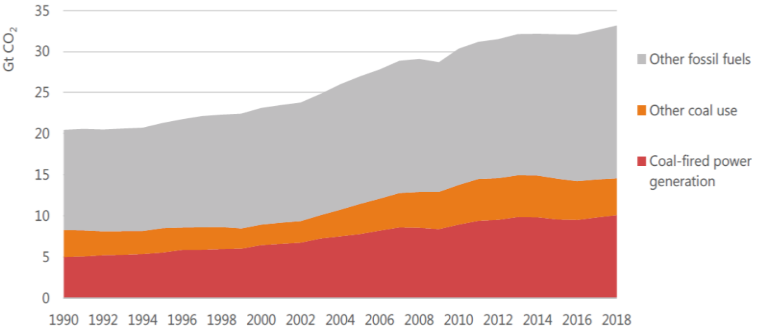


Figure 6.4 Global energy-related CO_2 emissions by source (Source: IEA, 2019c).

The power industry is the largest single contributor to energy sector GHG emissions, representing 36% to 37% of energy sector CO_2 emissions from 2000 to 2018 (Figure 6.). These emissions have been increasing. Transport (excluding international shipping and aviation transport) accounts for less than one fifth (18.2% in 2017 and 2018) of the total fossil fuel emissions. While recent deployment of renewables in the power sector and the high growth rate of electric vehicles offer prospects for the decarbonisation of these two sectors, it is likely that petroleum products will remain the main fuels for road transport in most countries in the near future. Decarbonisation of shipping and aviation international transport present important challenges for decarbonisation (see Section 6.6), but account for less 3.5% of the total fossil fuel CO_2 emissions.

Figure 6.5 Fossil fuels CO_2 emissions by sectors (source Crippa et al., 2019)

Energy sector activities like coal mining, oil and natural gas production and biomass combustion contribute to around one-fourth of the total non-CO_2 emissions and their share in total GHG emissions has increased in past decade or so. Globally, in 2016, the share of CH_4, N_2O and F-gas emissions was 19%, 6% and 3% respectively. Further, energy sector activities like coal mining, oil and gas production contributed to around 25% of total CH_4 emissions (Olivier et al. 2017). If bioenergy use goes up, non-GHG emissions (N_2O and NH_3) could increase (Minx et al. 2018).

At present, China, USA, EU28, India, Russia and Japan account for 51% of global population, over 60% of GDP and total primary energy supply, contributing to around 68% of total fossil CO_2 emissions (Muntean et al., 2018). Since the beginning of the 2000s, Asia is the major contributor to GHG. In 2016, Asia accounted for 17.4 Gt of CO_2 (IEA 2018a) – that is, over 53% of the total emissions – mainly due to China and much lesser extent to India with respectively 52% and 12% of the total GHG emissions in the region. GHG emissions in China are fairly stable since 2013 after however an important growth during the period 2000-2013 (IEA 2018a). Unlike China, emissions in India are still growing at an average rate below 5% since 2010. Africa accounted in 2016 for just 3.5 % of GHG emissions although its emissions have doubled since 1990. The bulk of the emissions in Africa occurred in a limited number of countries mainly South Africa and North Africa.

6.3.2 Global energy demand and energy production continue to grow

Over recent decades, the global energy system has experienced substantial changes, most notably the deployment of renewable power generation, improved energy efficiency, the emergence of unconventional fossil fuels, particularly shale gas, and country commitments on mitigating greenhouse emissions. Despite their magnitude, these changes are not consistent with the rate of change needed to meet the Paris goals (see Section 6.7).

Recent changes in the energy system can be viewed within the context of longer-term trends in energy supply and use. Over the last fifty years, there has been a significant increase in total primary energy supply (TPES) and large structural changes in the sources of energy. TPES increased 2.5 times between 1971 and 2017, from 230 $EJyr^{-1}$ to 580 $EJyr^{-1}$. Production of fossil fuels has increased over that period, although there are significant differences in growth rates and relative contributions to total energy supply. The share of coal is 1% higher than it was in 1971 (27% against 26%), while the share of oil is substantially lower (32% against 44%), and the share of natural gas has increased (from 16% to 22%).

The growth of renewable energy over the last half century has been substantial, including large recent increases in wind and solar power deployment; yet the share of renewable energy in the energy system today remains small. The rapid increases in wind and solar power are relatively recent, started from low level, and are mainly confined to power generation. The share of nuclear energy is just 1% against 5% in 1971. Among other issues, the Fukishima accident has affected the global nuclear industry, causing many countries, to adjust their nuclear policies (Ming et al. 2016). Energy production of all fuels is concentrated. Over half of total energy production is located in 5 countries and in just 2 countries for coal and nuclear (IEA 2019a).

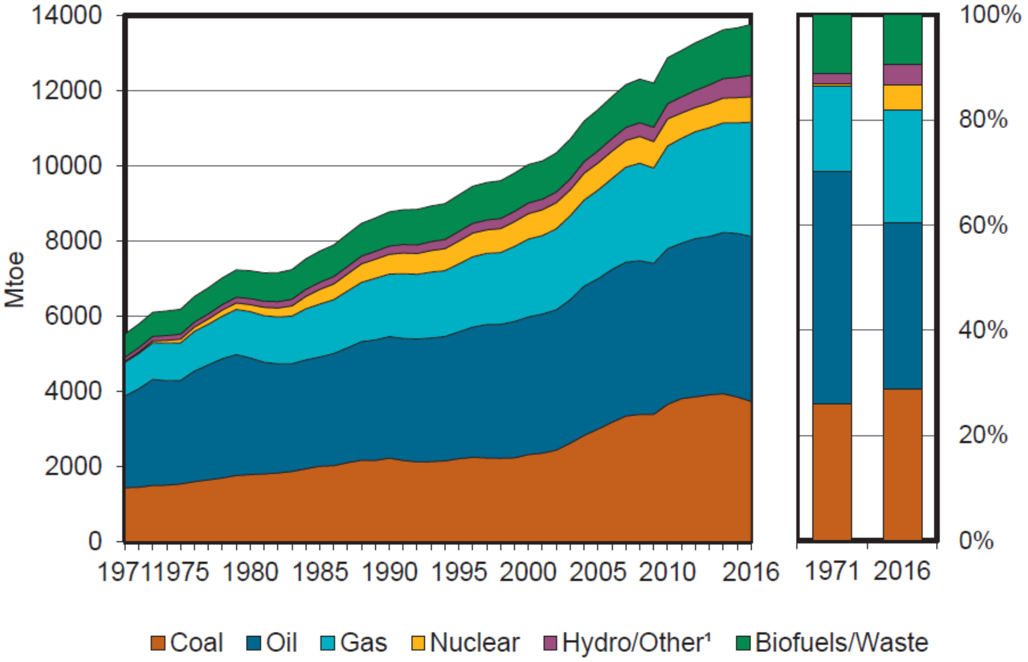


Figure 6.6 Total Primary Energy Supply (Mtoe and %) (Source IEA, 2018, World Energy Balances)

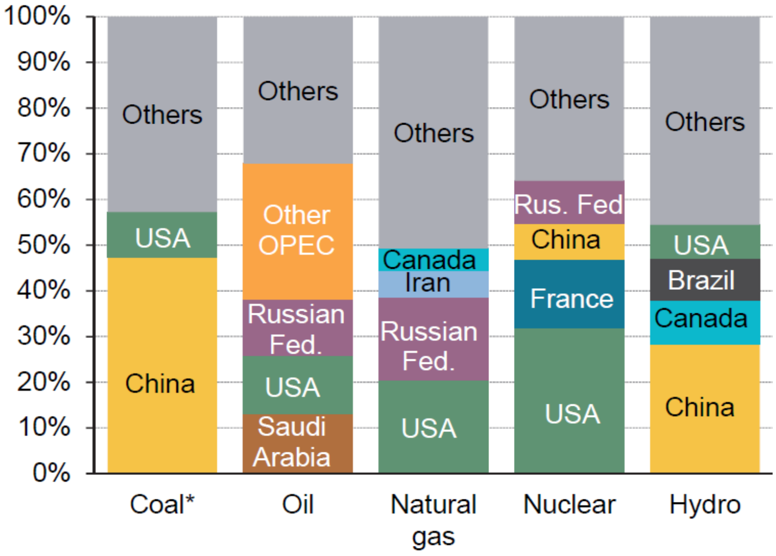


Figure 6.7 Country concentration of energy supply (%)

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. Africa is still characterized by a high share of biofuels (mainly fuelwood) in the total primary energy supply (TPES) as well in the final consumption particularly in the residential sector in sub-Saharan Africa for cooking. In 2017, biofuels and waste accounted for 45% of the TPES against 9.5% on average worldwide.

Hydropower capacity in 2018 was 1,290 GW and generated 4,203 TWh in electricity (IEA 2019a). This represented 16.4% of the world's electricity from all sources (IEA 2018b; IHA 2019). In 2018, China dominates the production of hydroelectricity with 695.9 GW, followed by the USA (245.2 GW) and Brazil (135.7 GW). Trends in new hydroelectric project have remained fairly constant since 2010, except over Asia, where China once again dominates new projects.

The total final energy consumption has more than doubled between 1971 and 2017, from 180 EJ/yr to 410 EJ/yr (230% from 1971 to 2017). High demand in Asia after 2000 has been particularly influential. In 2017, Asia accounted for more than a third of TFC. TFC has remained stable in the OECD. Despite a steady increase, Africa's TFC remains relatively low particularly in most sub-Saharan countries.

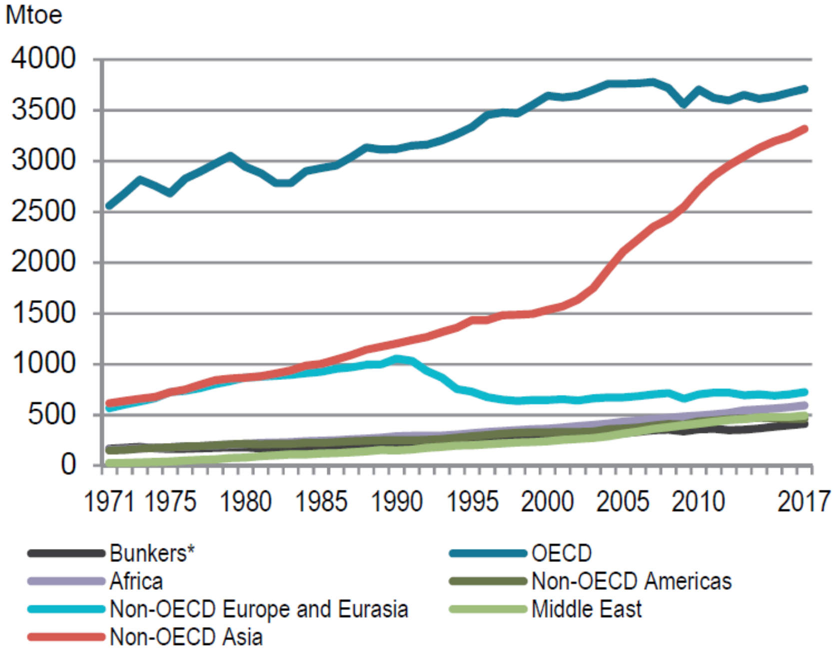


Figure 6.8 Total Final Energy Consumption by Region (IEA, 2019)

Transport accounted for 29% of TFC in 2017 as compared to 23% in 1971. The share of industry has barely changed between 1971 and 2017. The residential sector accounted for 21% of the TFC in 2017 against 24% in 1971.

Fossil fuels still account for an important share of the TFC (Figure 6.). Growth in transport has been important in driving oil use. Electricity increased during this period, which reflects better to access to electricity in developing countries and increasing use of electricity for a wide variety of different building services. Biofuels and waste (modern and traditional biofuels) still account for 42 EJ/yr. Biofuels (fuelwood and charcoal) are particularly important in the TFC of sub-Saharan countries and some Asian countries such as India.

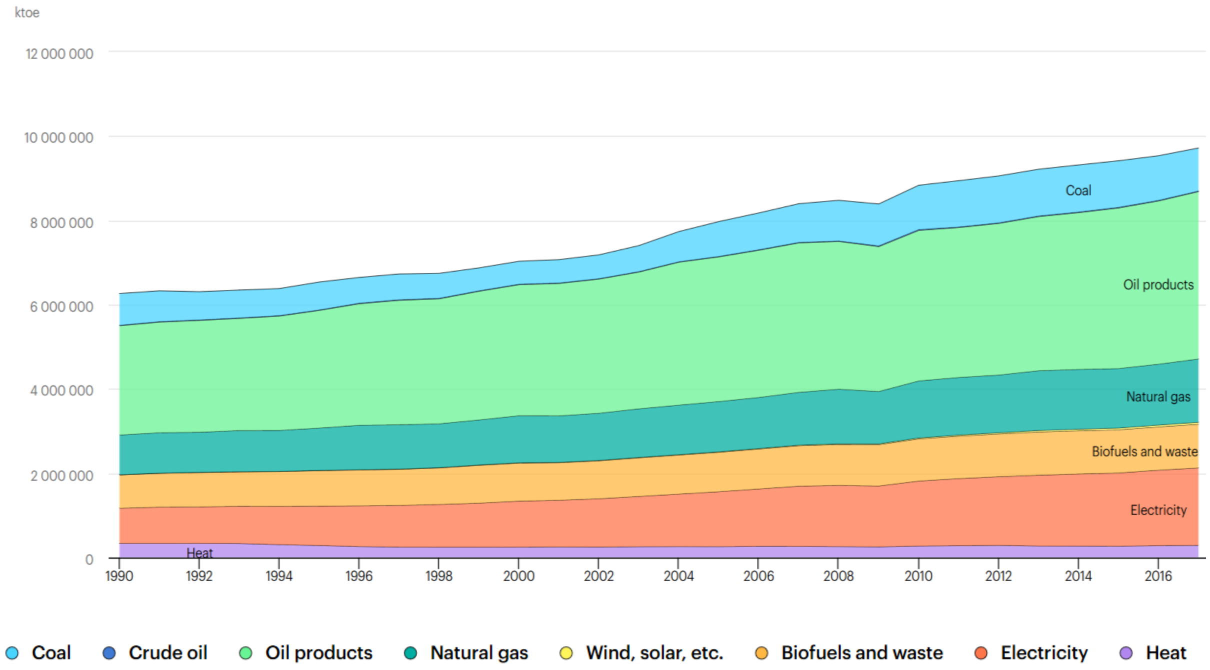


Figure 6.9 TFC by Energy Source (IEA 2019b)

Despite new international efforts, about 1 billion people still lack access to electricity and 2.7 billion to clean-cooking facilities. In terms of the universal energy access (SDG-7), the driving forces for future energy transitions in the domestic sector include new developments in off-grid energy technologies, emphasis on rationalizing energy subsidies and increasing concerns related to heath and climate.

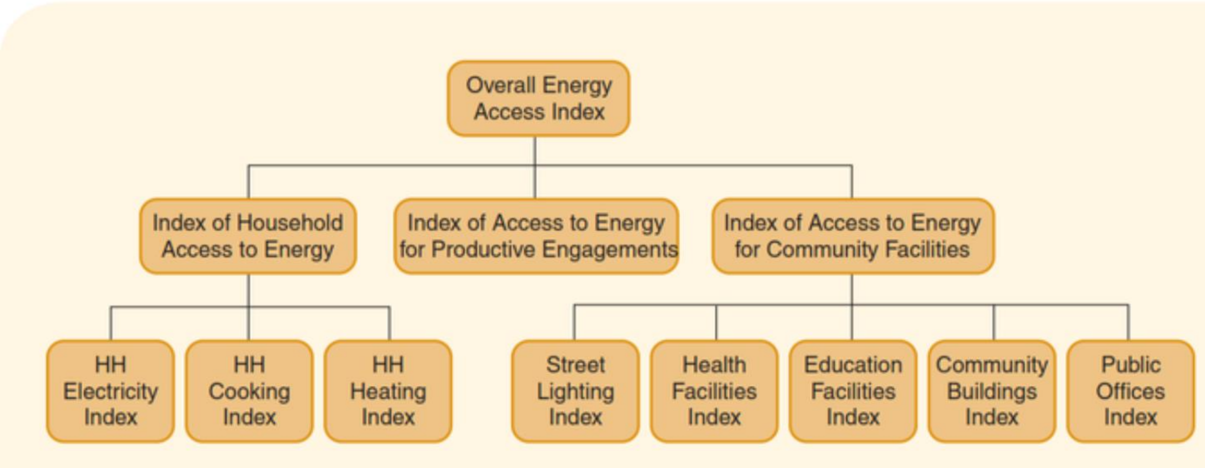
6.3.3 Non-climate factors continue to drive energy systems changes

While climate change is an important force in driving energy system changes, energy system evolution is linked to a much broader set of factors beyond climate change. Factors such as energy access, energy security, air pollution, and economic growth continue to exert a dominant influence on energy system decision making and evolution. [Placeholder-More detail will be added in the SOD.]

BOX 6.1 Energy access, energy systems, and sustainability

There is a large disparity in energy systems and energy consumption across the world. While this report focuses on greenhouse gas emissions mitigation, in a large number of 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-Sahara Africa and a few Asian countries. Successful mitigation must operate in tandem with fundamental development goals such as modern energy access.

The relationship between energy access and sustainability is embedded in a comprehensive framework summarized as the sustainable development goals (UN General Assembly 2015). 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 of all is universal access to clean and modern fuels.



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

Access to electricity is measured based on the capacity, duration, reliability, quality, affordability, legality and health and safety impacts. Despite progress in some populated countries particularly in India, Bangladesh and Kenya, the global population without access to electricity in 2017 was about 840 million against 1.2 billion in 2010. Access to modern energy for cooking is based on the indoor air quality, cookstove efficiency, convenience, safety of the primary fuel, affordability, quality of the primary fuel and the availability of the primary fuel. The population without access to clean cooking solutions totalled almost 3 billion in 2016 and was distributed across both Asia and Africa (IEA et al. 2019). In 2018, around 850 million people in sub-Saharan Africa rely on traditional biomass (firewood and charcoal) for cooking and another 60 million rely on kerosene and coal to meet their daily energy needs (IEA 2019a).

Based on the projections of current and planned policies the IEA estimates 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. A projected 650 million people are likely to remain without access to electricity in 2030 out of which 90% will reside in Sub-Saharan Africa (IEA et al. 2019). According to IEA decentralised renewables with 54% and on grid renewables (27%) are the least cost options to provide universal access to electricity by 2030. As far as cooking is concerned, in its sustainable development scenario (this scenario universal access will not be reached by 2030) natural gas (26%), LPG, kerosene and improved biomass cookstoves will account for 86%.

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. 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. This is feasible over the next 20 years, provided that sufficient financial resources are made available for investments on the order of US$36 billion to US$41 billion/year (Riahi et al. 2012) half of it in Africa).

6.3.4 Initial efforts to phase out coal while overall consumption continues to grow

The use of freely-emitting coal is particularly important in the context of climate mitigation. Coal consumption declined globally for several years through 2016, but then began to increase again in 2017 (Figure 6.) There are two important trends at play in the context of coal consumption. On the one hand, coal use has been declining in major consumer countries in large part due to environmental regulations and inexpensive shale gas especially in the United States. Older coal fired power stations that cannot meet new environmental regulations have been phased out. Air quality concerns in China have led to a shutdown of coal fired industry and power generation around the major cities. There have been some government-imposed moratoriums on new coal generation construction (e.g. Canada). On the other hand, coal use continues to increase in a number of developing countries such as Vietnam, the Philippines, Malaysia, India, Colombia and Indonesia. China, US, Australia and South Africa still remain at a high level of coal extraction and use. In most developing countries with abundant coal reserves, coal use has been increasing given the energy security it provides and the relatively lower upfront capital investment.

Major coal using countries are still some distance from phasing it out (Spencer et al. 2018). Myriad challenges exist including lower depreciated capital costs of existing coal based plants, not internalizing externalities of coal use, and not increasing business risks for coal sufficiently high (Garg et al. 2017). Cheap coal is the choice of fuel in all fast developing growing economies in Asia led by China and India (Steckel et al. 2015).

Coal transitions have been observed to be happening in some regions, with larger scope of tailored reemployment. A just transition to the workforce is possible with estimates showing larger employment opportunities associated with cleaner forms of energy. For instance, fossil fuels are estimated to generate 2.65 jobs per $1M as compared to projected 7.49 from renewables (Garrett-Peltier 2017). Moreover, future energy sector jobs may be in tandem with bioenergy agriculture which might not only reduce the loss of coal employment but create new jobs (Patrizio et al. 2018; Tvinnereim and Ivarsflaten 2016).

While some regions have demonstrated coal phase out with dedicated policies to initiate these, there is also a trend of increased number of coal plants in other regions (with delayed peaking of coal use). Similarly, natural gas power plants have rapidly scaled up made possible by large unconventional gas developments (Kriegler et al. 2018a) (van Vuuren et al, 2015) – exacerbating risks of large fugitive methane leakage. This is directly in contrast with the pathways shown in the literature, where it is observed that in various pathways for a 2ºC scenario, unabated fossil fuel consumption does decline in all scenarios by significant margins below renewables.

BOX 6.2 Status and Challenges of a Coal Phase-Out

Despite a global increase in coal production of 1.7% between 2016 and 2018, several countries and regions have committed to, or operationalized coal phase-out (Watts et al. 2019). While not at the level of the 5-7% annual reduction required to meet the 1.5°C target, these examples of coal phase-out give us an understanding of mechanisms of moving toward coal moratorium globally (Spencer et al. 2018). This includes profitable fuel switching (to gas or renewables), strong policy choices or other considerations such as health and electricity access. Many financial institutions and pension funds have committed not to fund new initiatives on coal or coal-based infrastructures, and have a carbon tax in the range of USD 35-45 per ton CO_2 for assessing any new investment proposal (Nie et al. 2016; World Bank et al. 2017).Countries on the other hand mostly give priority to policy-based interventions for coal phase out. We discuss such cases from around the world below.

Europe: A number of European countries are part of the Powering Past Coal Alliance (PPCA) and they have committed complete coal phase-out on or before 2030. These countries, though, have a cumulative capacity of only 43 GW and are economically developed and thus opting for alternative energy routes is easier. Moreover, pre-mature retirement is rare even for these countries (Jewell et al. 2019). On the other hand, around 70 GW of coal capacity exists in Germany and Poland. These two countries also account for two-thirds of the coal subsidies in Europe and therefore, operationalizing coal phase-out here is critical for meeting climate goals (Whitley et al. 2017). A major issue for phasing-out coal here is institutional lock-in and it is suggested that complete phase-out may be possible only financial instruments, such as in the example of the UK (Rentier et al. 2019). The German government appointed in 2018 a commission for growth, structural change and regional development in order to develop a roadmap and end date to phase out coal-fired power plants. The recommendation was to phase out the use of coal for electricity generation by 2038 latest. The recommendations of the coal commission include compensation for power plant closures, labour market measures for coal workers, protection against rising electricity prices for industry and substantial support structural change for coal-mining regions. These are currently implemented by the German government. The narrative of coal phase-out in Europe also focusses on a just transition for workers (Johnstone and Hielscher 2017; Osička et al. 2020). Further, because of high historical emissions, coal phase-out alone will not lead to adequate decarbonization in Europe and it must be supplemented by renewables and NETs (Heinrichs and Markewitz 2017; Heinrichs et al. 2017; Figueiredo et al. 2019).

North America: A very prominent case of coal phase-out has been seen in North America, where availability of cheap shale gas has reduced coal use by about 36% in US and 50% in Canada in the last decade (Dolter and Rivers 2018; EIA 2019). This compounded with cheap renewables or environmental regulations in particular regions shows that even with inclusion of CCS, coal use is projected to decline here (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 and air pollutants and cooling water use (Harris et al. 2015; Kondash et al. 2019). However, there have been concerns regarding employment of coal workers. For instance, in the US, phase-out has led to decreased employment of about 30,000 workers with notable regional and economic inequities (Bodenhamer 2016; Abraham 2017; Greenberg 2018). It is projected that, if sustainably managed, there may possibilities of reemployment or even additional employment by diversification of the industry, say through BECCS (Patrizio et al. 2018; Homagain et al. 2015)

China and India: China and India are the highest coal producers and have no committed phase-out plan yet. However, a phase-out here will encompass several health benefits especially as regards to air pollution reduction (Peng et al. 2018; Dholakia et al. 2013; Singh and Rao 2015). In China, there was an announced coal moratorium in 2015 which was also predicated on cutting overcapacity (Blondeel and Van de Graaf 2018). However, there has been a recent coal capacity addition as well as announcement of new coal licenses there. In India, there has been no committed coal phase-out but rural electrification efforts and renewables push of the government may lead to preferential investments in the solar and wind sectors (Aklin et al. 2017; Thapar et al. 2018). However, India has retired about 8.5 GW of inefficient and old coal based plants between 2016 and 2019 (CEA 2019). Notably, 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). In addition, India has also cancelled over 50% of their proposed new coal plant capacities since 2016 (Monitor Global Energy. 2019)

Africa: There has been considerable upswing in the announced coal projects in Africa. 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 mid-century, as compared to the current levels of 77,000 (Strambo et al. 2019; Cock 2019). As South Africa has the largest income inequality, creating a sustainable transition for these workers is essential through reemployment in the growing renewable sector (Swilling et al. 2016).

In terms of the varieties of coal phase-out, it is useful to demarcate the mechanisms driving the move away from coal – whether market-driven, policy cap or societal benefits. These examples also enable a better forecasting for the anticipated volatilities in the oil and gas sector, where phase-out is not immediate but imminent in the 2°C scenarios (Raimi et al. 2019).

6.3.5 Solar and wind generation grow dramatically, but less than needed to meet the Paris goals

In the past fifteen years, the levelized cost of electricity (LCOE) from renewable energy sources has dropped dramatically and deployment levels have increased around the world. Power generation from solar PV increased by more than 25% in 2018, to over 480 TW. Despite this growth, however, solar remains the fourth-largest renewable electricity technology in terms of generation, after hydropower, onshore wind, and bioenergy, exceeding 2% of total power generation for the first time only in 2018.

The recent growth in solar energy has occurred in developed economies as well as emerging Asian economies. Yearly installations in Europe have declined since their highest historical value of 22 GW of new capacity additions in 2011. In 2018, the share of total global cumulative capacity of Europe decreased to 25%. Recent growth in the Asian PV market, especially in China, Japan and India, has more than compensated for the decrease in new capacity additions in Europe. At the end of 2018, Asia Pacific was home to 60% of global installed capacity, and China is the world leader in PV production. The United States has also become a large PV market. India has great potential for development, with the highest growth rate of 102% in 2017 alone. The countries with the largest cumulative installed capacity globally are China (34%), USA (10%), Japan (12%), Germany (9.4%) and India (5.6%).

There are substantial regional differences in PV deployment due to underlying differences in solar resources (see section 6.4) (Breyer et al. 2017). Thus, most rapid growth has been seen in the U.S. and E.U. However, future trends indicate a much-increased uptake in developing countries like China and India, consistent with the NDCs of such countries. A major advantage of such adoption will include the diverse application of PV, including in providing off-grid village electrification (Sahoo 2016). Moreover, it has also been indicated that increased solar penetration in the electricity sector could, in the right conditions, give rise to improved performance of health and water desalination systems, indication crucial linkages to the sustainable development goals (Sampaio and González 2017; Dholakia and Garg 2018).

Table 6.2 Cumulative installed photovoltaic (PV) power (MW) by region and six leading countries, 2018 (Source: IRENA 2019a).

Region	Cumulative installed	Growth rate of 2018	Share in 2018
Total World	480 619	25.4%	100%
Asia Pacific (Asia + Oceania)	285 248	33.8%	59.4%
China	175 016	33.8%	36.4%
Japan	55 500	25.5%	11.5%
India	26 887	50.0%	5.6%
Europe	118 840	7.7%	24.7%
Germany	45 277	6.9%	9.4%
Italy	20 120	2.2%	4.2%
North America	55 386	23.2%	11.5%
USA	49 692	20.2%	10.3%
South & Central America and Caribbean	7 197	46.5%	1.5%
Africa	5 122	35.6%	1.1%
Middle East	3 125	50.5%	0.7%
Eurasia (former CIS)	5 701	53.0%	1.2%

CSP has also continued to grow, but it remains far less important in solar generation than PV. In 2018, the total installed capacity of CSP reached 5.5 GW, relative to 4.8 GW in 2015. Production remains in a limited number of countries with high DNI. In Europe, almost all CSP are located in Spain. Almost 75% of total installed capacity is in Spain and the U.S.

From the initial wind energy exploitation in a few countries in Europe and in the USA, more than 90 countries have now commercial operations. More than 9 of them with more than 10,000 MW in Europe, North America, Asia and South America (GWEC 2019). Total global cumulative capacity was 580 GW (IRENA 2019a; GWEC 2019) (Figure 6.). Over 95% of installed capacity is onshore. The four largest wind energy installed capacities are now in China (approximately 180 GW), the USA (approximately 94 GW), Germany (approximately 53 GW) and India (approximately 35 GW) (IRENA 2019b).

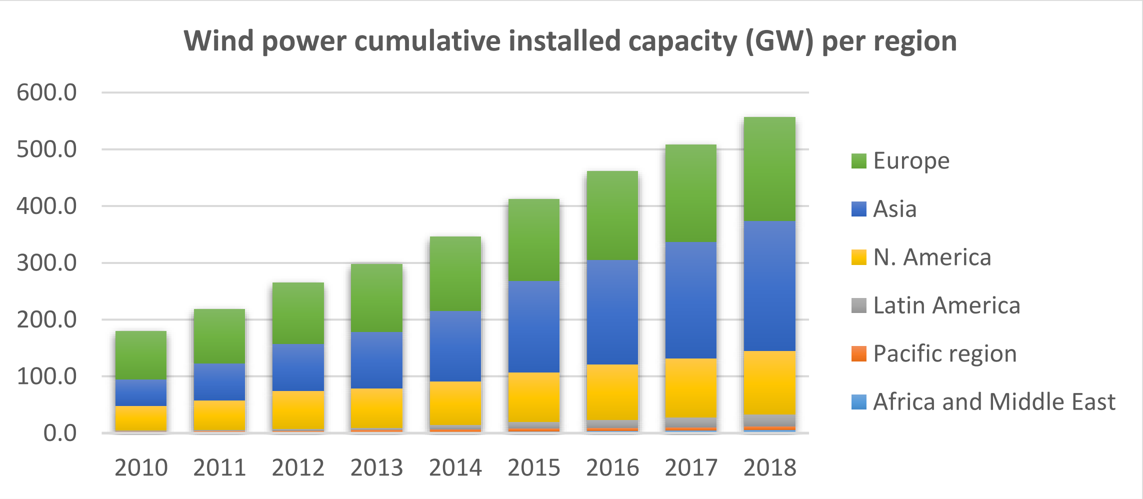


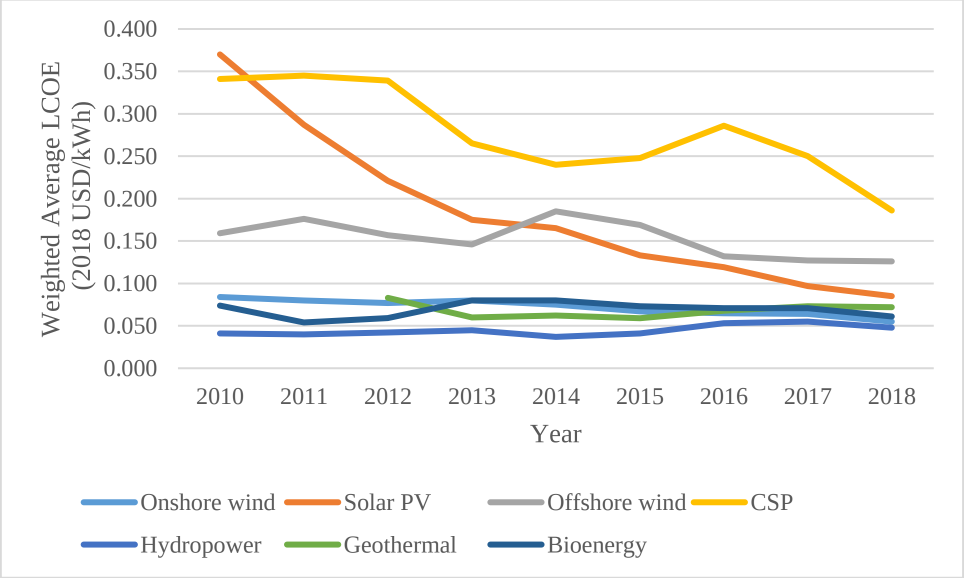
Figure 6.10 Global wind power cumulative installed capacity (on- and offshore) from 2010-2018 per region. Source: (IRENA 2019a).

The years of 2017 and 2018 saw newly added capacity of 54 GW and 51 GW, respectively (GWEC 2019), of which 9 GW was offshore. The largest additions per region occurred in Asia. China installed 24 GW and 25 GW of new wind in 2017 and 2018. The rate of new onshore installations in Europe decreased by nearly 35% between 2017 and 2018, mainly driven by decreases in new installations in Germany and the UK. New offshore installation increased slightly in 2018 compared to 2017, with the largest additions in the UK (1.7 GW and 1.3 GW) and China (1.2 GW and 1.8 GW).

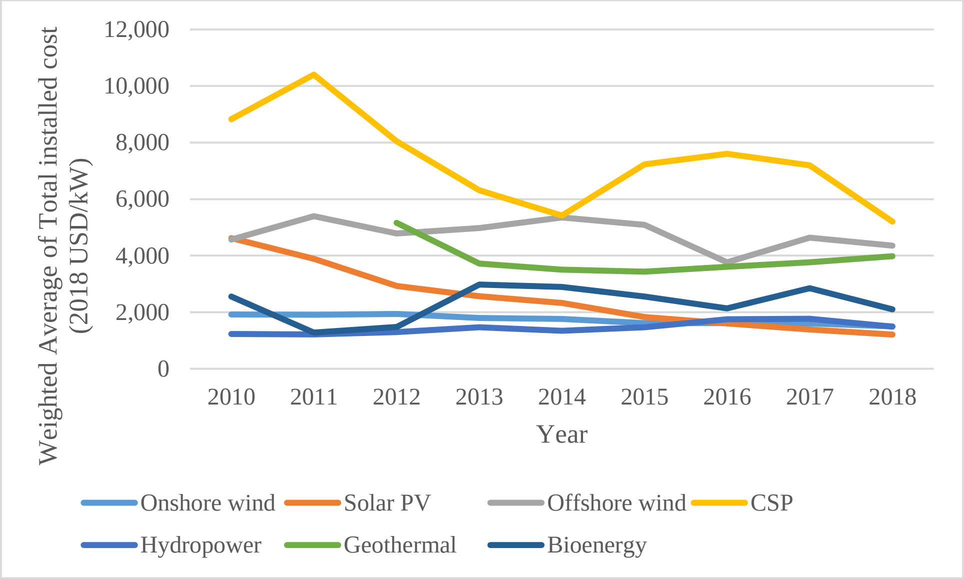
The largest wind energy generation of electricity per continent was recorded in 2018. For this year, wind turbines in Europe supplied 14% of the EU's electricity demand (Wind Europe 2018). The highest wind energy penetration rates were 41% in Denmark, 28% in Ireland, 24% in Portugal and 21% in Germany.

BOX 6.3 Recent reductions in renewable generation costs

Since, 2010, the levelized cost of electricity (LCOE) for mature renewable energy technologies like bioenergy, hydropower, geothermal and wind (offshore and onshore) have remained competitive with corresponding costs from fossil fuel-based power. LCOE for solar PV has fallen sharply in past five year and is also now competitive with fossil fuel electricity. According to the International Renewable Energy Agency, renewable costs, especially for solar PV and wind, have reduced due to technology innovations followed by rising investments in these technologies. This has led to increased deployment of these renewable sources (BNEF 2019; IRENA 2019c).



Box 6.3, Figure 1 Technology wise evolution of RE based electricity costs



Box 6.3, Figure 2 Technology wise evolution of RE based electricity costs

Source: Adapted from IRENA RE costs database (IRENA 2019b).

Between 2010 and 2018, the global average levelized cost of electricity (LCOE) generated from utility-scale solar PV, onshore wind and offshore wind has declined by around 77%, 35% and 21%, respectively. Further, global average installed costs of solar PV have also declined by around 74% between 2010 and 2018 for utility-scale projects.

In case of other technologies like hydropower and bioenergy, the costs have remained steady because available technologies for these sources are already at a mature stage. On the other hand, if technologies are at a nascent stage of development with limited investments in them, such technologies too exhibit a limited decline in costs. Renewable energy costs also vary by region depending on availability of renewable resource like sunlight, wind and biomass along with institutional and policy mechanisms to support the growth and development of renewable technologies (Best and Burke 2018; Gupta et al. 2019; Wagner et al. 2015). For instance, China and India have very low LCOE of solar PV based power due to ample availability of resources while corresponding costs in EU are one of the highest due to poor resources of solar and wind energy. Similarly, wind power is one of the cheapest in the USA due to high availability of resources and a well-developed market for wind generation (IEA 2018a; IRENA 2019b).

Finally, the costs of electricity storage are crucial for integrating intermittent sources like solar and wind in utility-scale electricity systems (Arbabzadeh et al 2019; Braff et al. 2016). At present, energy storage is dominated by pumped-storage plants which accounted for 96% of all electricity storage. However, battery electricity storage is catching up and according to a study, between 2007 and 2014, the industry-wide cost estimates of Li-ion battery packs declined by 14% annually, from over US$1000 per kWh to less than US$ 410 per kWh (Nykvist et al. 2015).

6.3.6 Limited deployment of low-carbon energy sources beyond solar and wind power

While low- or zero-emissions sources have been growing as a percentage of global primary energy, most of this growth has been in wind and solar power. Nuclear power has been declining and faces a number of obstacles to more widespread deployment. CCUS deployment has been limited. Bioenergy production has grown from xx% to yy% over the last decade. Geothermal power continues to expand, but at limited rates and is not expected to contribute a substantial share of future energy production in most regions.

Nuclear power is used in 30 countries. By the end of 2018, there were 450 operational nuclear power reactors with a total net installed capacity of 396 GW(e) (IAEA 2019a). Despite historically the highest available power, the share of nuclear power in total electricity production has been declining from 17.4% recorded in

1996 to around 10% in 2018. Main factors for this drop was a slow-down in the rate of commissioning of nuclear reactors and a surge of electricity demand in developing countries, which, to a large extent, was met by fossil fuels. Nuclear power still plays a big role in advanced economies, where it makes up 18% of total and 40% of low-carbon electricity generation (IEA 2019c). The bulk of nuclear reactors (50%) is located in the USA (96), France (58), Japan (37) and Russia (36).

At the end of 2018, 2/3 of the operating nuclear power reactors had been in operation for over 30 years. A nominal design lifetime of a typical NPP is of 40 years, but engineering assessments have established that many can operate safely for longer if key components are replaced and refurbished. Long term operation and aging management programs are being implemented for an increasing number of nuclear power plants (IAEA 2019a). Lifetime extensions require significant investment (in the range of USD 750-1200 per kW) but are one of the most cost-effective ways to provide low-carbon sources of electricity through to 2040 (IEA 2018c)(EPA, 2019; IEA, 2019). Thus, the contribution of nuclear power to GHG emission reduction will depend in part on how countries decide to deal with existing nuclear power plants.

There are 55 units under construction in 18 countries, which would add a total power of 53.8 GW. Most of these new builds (35) are located in Asia (e.g. 10 in China, 7 in India), which is also home to 58 of the 68 new reactors that have been connected to the grid since 2005 (NTR, 2019). There are also 29 "newcomer" countries at different stages of nuclear power programme development/consideration (IAEA, 2019a). The shift in the center of gravity to developing countries, in particular to Asia, has been visible over the last two decades, and is expected to continue in the near and long term. It is driven by underlying fundamentals of population and economic growth and electricity consumption, as well as concerns related to climate change and air quality, security of energy supply and price volatility of other fuels.

According to the IAEA estimates, the world nuclear electrical generating capacity is projected to increase to 493 GW(e) by 2030 and to 715 GW(e) by 2050 in the high case. In the low case, the world nuclear electrical generating capacity is projected to gradually decline until 2040 and then rebound to 371 GW(e) by 2050 (IAEA 2019b). The high and low case estimates are based on an extensive project by project experts' analysis of possible license renewals, planned shutdowns and plausible constructions foreseen for the next decades reflecting realistic capabilities of equipment providers/vendors, stated national plans and expected global climate change mitigation trends. The low case assumptions are in line with business as usual whereas the high case is more ambitious but plausible and technically feasible.

The wide range between the low and high projections is due to uncertainty regarding the replacement of the large number of reactors scheduled to be retired around 2030 and beyond, particularly in North America and Europe. With more life time extensions assumed in the high case, new additions to 2030 average to 12 GW(e) per year by 2030 and almost 18 GW(e) per year by 2050. New connections to the grid recorded in the last 5 years (2014-2018) amount to an average of 7.5 GW(e) per year suggesting that currently nuclear power deployment falls short of its potential.

Although plans for CCUS are increasing, CCUS remains largely in the demonstration phase without a meaningful impact on CO_2 emissions. There are now a number of ongoing and upcoming CCUS projects (43 in 2018). New facilities may capture up to 13 Mt CO_2 annually. CCUS facilities may further increase in future with policy initiatives to tax carbon tax and promote low-carbon energy use (IEA, 2019). Clear policy directions, potentially including market mechanism (e.g., through a carbon price), are required for scaling up CCUS options for a transition towards low-carbon future.

Geothermal energy output in 2018 was estimated at 630 petajoules, with around half of this in the form of electricity (89.3 terawatt-hours (TWh)) and half as heat (REN 21, 2019). Geothermal for electricity generation is concentrated in a limited number of countries. The prospects for large scale developed in the next decade are relatively limited. The market for geothermal remains modest, with between a minimum of 90 MW (in 2011) and a maximum of 650 MW (in 2015) of annual new capacity commissioned between 2010 and 2018 (IRENA 2018). An estimate of just 0.5 GW of new geothermal power generating capacity came online in 2018, bringing the global total to around 13.3 GW. Global geothermal power capacity is expected to rise to just over

17 GW by 2023, with the biggest capacity additions expected in Indonesia, Kenya, Philippines and Turkey (IEA 2018d).

6.3.7 A rapid evolution in energy storage

Energy storage includes battery storage, pumped hydro, hydrogen and compressed air. It is projected to be a prominent part of future energy systems globally for improved renewable integration into the grid (IPCC 2014; Denholm and Mai 2019). As renewable penetration increases beyond 80%, synthesis work projects that storage requirements will be 0.2-6 TWh/yr in the US and 0.2-22 TWh/yr in Europe (Cebulla et al. 2018; Zerrahn et al. 2018). These improvements will have substantial ramifications for energy system, particularly in transport and integration of renewable electricity.

Currently, the costs of electrochemical storage are considerably high, because of which their use is limited to off-grid applications (Agnew and Dargusch 2015). With added investments in storage, the costs are envisaged to radically decline over both electrochemical and other forms of energy storage (e.g. hydrogen, compressed air). Based on economic forecasts, these may be influenced by learning i.e. the amount of infrastructure already installed. Thus, capital costs are projected to decline towards $ 340±60/kWh for stationary systems and $ 175±25/kWh once 1 TWh capacity is installed (IPCC 2014; Kittner et al. 2017; Nikolaidis et al. 2019; Schmidt et al. 2019). However, to reach such installation levels cumulative investments of US$ 175-510 billion would be required by 2040 (Schmidt et al, 2017). It is noteworthy that multiple storage strategies are needed because they may serve separate purposes. Thus, lithium-ion and lead-acid batteries, which have the highest installed levels currently, are not suitable for seasonal storage and long-duration discharge which may be better served by pumped hydro or compressed air storage. Overall, storage costs may be anticipated to halve by 2050 to ~$ 250/MWh levels (Abdon et al. 2017; Jülch 2016).

It is important to place these costs in the context of the benefits that could be gained from large-scale availability of storage. For instance, both energy systems modeling and environmental economics literature demonstrate that beyond 2025, electricity storage would be beneficial in showing reduced CO_2 emissions. This is largely achieved by supply responses of coal transitions (Section 6.7.4) and avoided curtailment costs across countries (Linn and Shih 2019; Craig et al. 2018; Vishwanathan et al. 2018). There is also added evidence showing that the value of storage is as high as US$ 193-572/MWh when targeting tighter CO_2 constraints (De Sisternes et al. 2016). There is also further evidence of enhanced value of storage once such systems begin to participates in reserve markets instead of just providing arbitrage (Staffell, I. and Rustomji, M. et al. 2016; McConnell et al. 2015). Some concerns have been raised on end of life environmental concerns from large scale deployment of storage technologies (Oliveira et al. 2015; Hertwich et al. 2015).

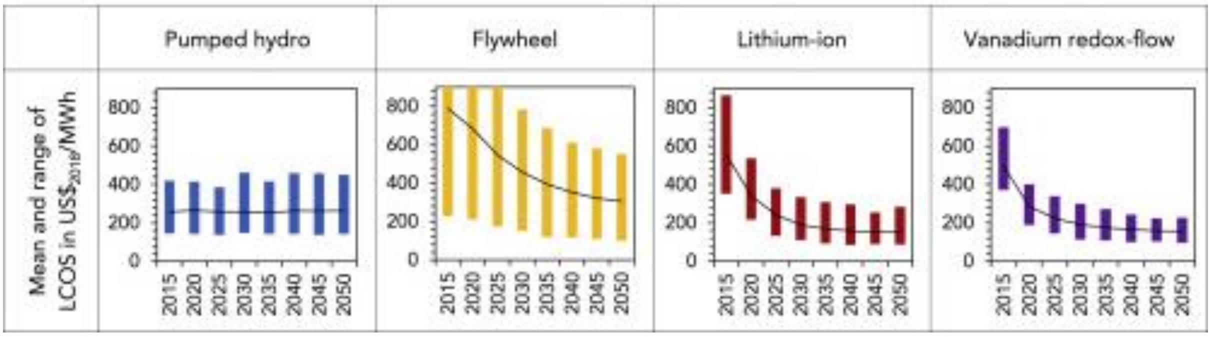


Figure 6.11 Projections for future levelized costs of storage for various technologies (Schmidt et al, 2019)

In the literature cited above, there is a consensus that improved battery lifetimes and deeper discharge times have considerable forecasted improvements on the storage costs of most electrochemical storage. For lithium ion batteries, there is also a need for reduced material costs (Pierpoint 2016). The challenges are somewhat more diverse for pumped hydro storage and compressed air storage where geographic and geological challenges are also considered (Mouli-Castillo et al. 2019). Finally, it is important to consider that the role of storage is an important but its optimal usage will involve operation of energy systems in tandem with other approaches such as net metering, flexible operation and supply-demand matching (Abdin and Noussan 2018; Weitemeyer et al. 2015; Hohmeyer and Bohm 2015).

6.3.8 The energy policy landscape continues to evolve

There are many policies and institutions that are relevant to the energy sector. These include regulatory instruments like command and control, sectoral efficiency standards along with economic instruments like carbon taxes, subsidies and emissions trading schemes. In addition, there are other policies and institutional mechanisms like information policies, government interventions to provide public goods and services and voluntary actions by citizens, businesses and other non-government actors (Somanathan et al. 2014). A number of important energy policy trends have emerged in recent years (Table 6.3)

Many national and sub-national governments from across the world have started relying on regulatory and other fiscal instruments to achieve their climate goals (Bertram et al. 2015; Martin and Saikawa 2017). In developing countries, instruments besides carbon pricing like efficiency and fuel standards, subsidies on clean energy technologies and public programs to promote low-carbon infrastructure are more popular as the costs of these instruments are not generalized and less visible. If designed well, redistributive effects are not too regressive (Finon 2019).

Table 6.3 Recent trends in climate-related energy policies around the world

#	Policy Category	Instruments	Country examples
1	Command and Control Instruments	• Energy Efficiency Standards • Technology Phase-out mandates	• Building codes, household appliance standards and labels, phasing out of old vehicles and coal power plants in China, India, USA and EU • Zero Emission Vehicles regulations in China, EU
2	Flexible regulation-based standards	• “Baseline-and-Credit” regulations	• Energy efficiency programmes for energy-intensive industries in USA, China, Mexico • Perform, Achieve and Trade (PAT) scheme for energy-intensive industries in India
3	Subsidies in clean technologies	• Capital subsidies to manufacturers • Cash transfers to consumers	• Subsidy for setting up renewable power plants in China, Germany, India • Subsidy for energy access (LPG, electricity, kerosene) to poor households in developing countries
4	Renewable Energy	• Renewable Portfolio Standards • Renewable Energy Certificates • Feed-In-Tariffs	• Feed-in-tariffs, feed-in-premiums, renewable purchase obligations and other incentives being implemented in over 160 countries
5	Public Infrastructure Programmes	• Investments in public transport, Electric Charging Infrastructure • Urban Planning programmes • Upgradation of electricity grid infrastructure	• Mass Rapid Transit Systems, railways in India and China • EV infrastructure in EU countries • India’s programme for technology upgradation in electricity grids to reduce transmission and distribution losses

Sources: (Berardi 2017; Bertram et al. 2015; Finon 2019; Gupta et al. 2019; Martin and Saikawa 2017; Wong and Karplus 2017)

Governments have chosen a mix of policies and institutional mechanisms that consist of non-market-based instruments (e.g. command and control regulation, information and voluntary approaches, active technology support) and economic instruments (e.g. subsidies, investment in public goods). The choice of policies has depended on institutional capacities, technological maturity and other developmental priorities of governments. It is also found that governments favour regulatory instruments over fiscal policies like taxes, subsidies and feed-in-tariffs when it has sufficient institutional capacity to implement and monitor the regulations and standards (Hughes and Urpelainen 2015). Climate-related energy policies are driven by a combination of regulatory, fiscal and market-based instruments depending on the market conditions and technological maturity.

For example, fiscal instruments like feed-in-tariffs (FIT) work when the technologies are in nascent stages of development and their effect may start declining as the technologies mature (Gupta et al. 2019). On the other hand, for more mature technologies, market 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) An analysis of 137 countries over the period of 2005 to 2014 found that policy instruments like Feed in Tariffs (FIT) followed by fiscal measures like tax incentives and renewable portfolio standards (RPS), have played a significant role in attracting foreign direct investments in renewable energy sector, globally (Wall et al. 2019). Another analysis suggests that 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).

Economic instruments like carbon taxes and emissions trading schemes (ETS) have been considered as key policy instruments to address climate change since early 1990s. Researchers have argued that carbon pricing can help achieve the climate goals in a cost-effective manner, as compared to other policy instruments (Haites 2018; Baranzini et al. 2017). Many suggested measures to improve the performance of ETS and carbon pricing (Bataille et al. 2018; Campiglio 2016) Goulder and Morgenstern, n.d.). According to a recent report (World Bank 2019), 57 regional, national and sub-national carbon pricing instruments, representing only 20% of the global GHG emissions, are in action or scheduled for implementation by 2020. However, after 2010, a number of national and sub-national carbon pricing initiatives have been abandoned due to changing political and economic situations in Europe and North America (Harrison 2018; Rabe 2018). Over 51% of these emissions covered are priced at less than USD 10 per tonnes of CO_2 equivalent (tCO_2e). 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). However, at present, only 5% of the global emissions covered under carbon pricing initiatives are consistent with this suggested range of carbon prices (World Bank 2019).

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. 2018a). 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”. Supplementary border carbon adjustments can be successful in protecting upstream industries (Schenker et al. 2018). Apart from the regulatory and fiscal instruments, implicit carbon pricing mechanisms like fossil fuel taxes and removal of fossil fuel subsidies are used by many countries as part of their climate policies. Fossil fuel subsidies can be seen as negative carbon taxes that encourage the use of carbon intensive fuels like coal and crude oil. In 2017, the global fossil fuel subsidies were USD 340 billion, according to a joint IEA-OECD pre-tax estimate. Between 2013 and 2017, the subsidies have gone down by around 50%, according to two independent assessment done by IEA and IMF (World Bank 2019) (see box on Energy Subsidies).

[BOX 6.4 STARTS HERE]

BOX 6.4 Recent developments in energy subsidies

Energy subsidies can be defined as measures taken by a government, or its authorized agency, in the energy sector to lower the prices for consumers, raise the prices for producers or lower the costs of energy production (IEA 1999). An analysis of subsidies across the world reveals that there are at least 17 different types of direct and indirect energy subsidies (Box 6.4, Box 6.4 Table), primarily directed towards lowering the cost of production (Sovacool 2017).

Box 6.4 Table 1 Types of energy subsidies (Source: Modified from Sovacool, 2017)

Type of subsidy/ Government intervention	Examples	Working mechanism		
		lowers cost of production	raises cost of production	lowers price to consumer
Direct financial transfer	Grants to producers (Nuclear Plants in the USA)	Y		
	Grants to consumers (Oil and electricity in Iran, Saudi Arabia, Egypt, China, India)			Y
	Low-interest or preferential loans (Solar PV, RE equipment manufacturers in China, India)	Y		
Preferential tax treatment	Rebates or exemptions on royalties, sales taxes, producer levies and tariffs (Tax relief on renewables in USA, EU, Japan, India)	Y		
	Investment tax credits (Solar and geothermal in the USA)	Y		Y
	Production tax credits (Wind power in Denmark)	Y		
	Accelerated depreciation (Wind power in India)	Y		
	State sponsored loan guarantees	Y		
Trade restrictions	Quotas, technical restrictions, and trade embargoes		Y	
	Import duties and tariffs (Solar PV in USA, India)		Y	
Energy-related services provided by government at less than full cost	Direct investment in energy infrastructure (Ports, oil and gas pipelines in USA, EU)	Y		
	Publicly sponsored R&D (RE in India, China, Germany, USA)	Y		
	Liability insurance	Y		
	Free storage of waste or fuel	Y		
	Free transport	Y		
Regulation of the energy sector	Demand guarantees and mandated deployment rates	Y	Y	
	Price controls and rate caps		Y	Y
	Market-access restrictions and standards		Y	

Subsidies can also be categorized based on energy sources – fossil fuels and renewables. In case of renewables, subsidies can be further classified into capacity and generation subsidies (Andor and Voss 2016). Capacity subsidies in renewables are mostly targeted at lowering the cost of production and developing a market for solar, wind or biomass-based generation. But majority of the renewable subsidies are generation-based incentives in the form of feed-in-tariffs (FIT). The incentives to generate solar and wind-based renewable electricity through FIT have resulted in large scale penetration of solar and wind capacities across the world (Best and Burke 2018). However, studies have also suggested that FIT is a suitable policy only till the technology matures (Gupta et al. 2019). On the other hand, FITs could result in welfare losses in some cases (Abrell et al. 2019) Andor & Voss, 2016).

A major chunk of energy subsidies is associated with fossil fuels. There are four prevalent methods for estimating energy subsidies – [1] program-based direct expenditures that measures government support to energy sector, [2] "price-gap" method which measures the difference between actual market-based price of energy and the one paid by end-consumers in a given jurisdiction, [3] "inventory approach" to the aggregate the financial and market support provided to an industry and [4] "externalities-based approach" which uses any of the first three methods and adds the cost of social and environmental externalities associated with the subsidies (Coady et al. 2017; Sovacool 2017; World Bank 2019).

Based on the method employed, the subsidy numbers can vary a lot. For instance, the estimated fossil fuel subsidies for the year 2017 were US$ 300 billion using IEA's pre-tax, price-gap method. On the other hand, the estimate for the same year was US$ 5.2 trillion as per IMF which employed the externalities based approach (World Bank 2019). According to the IMF (Coady et al. 2019, 2017), the global subsidies of US$5.2 trillion were equivalent to 6.5% of global GDP, a slight increase from 6.3% in 2015. In terms of country level assessments done using IMF's externalities approach, the largest subsidizers in 2015 were China (US$ 1.4 trillion) followed by USA (US$ 649), Russia (US$ 551), European Union (US$ 289) and India (US$ 209).

In addition, some subsidies are specifically targeted to enhance the provision of modern energy source, like electricity and cooking gas, in poor countries. In some cases, these energy access subsidies have helped in extending modern energy sources to the poor (ex. (Kimemia and Annegarn 2016)). A massive conversion program from kerosene to LPG in Indonesia shows that the degree of LPG adoption is strongly correlated with household income and the age of the cook. As a result, the Ministry of Energy and the World Bank launched the clean Stove Initiative targeting rural and remote areas (Thoday et al. 2018). However, in most other cases, the subsidies have proven to be regressive with little benefit reaching to the poor (Lockwood 2015; Sovacool 2017).

There are adverse environmental, economic and social consequences of fossil fuel subsidies (Rentschler and Bazilian 2017). The estimates of energy subsidies from 191 countries in 2015 (Coady et al. 2017), followed by recent updates (Coady et al. 2019), suggest that over 75% of the distortions created by fuel subsidies are domestic and reforming them can have substantial benefits within the country. The biggest distortion comes from under-pricing of local air pollution (48%), followed by GHG emissions (24%), road congestions and accidents (15%), and undercharging for consumption taxes and supply costs (14%). In terms of fuels, coal and oil account for 85% of the total subsidies. The study also suggests that if fuel prices were to internalize all the externalities in 2015, global carbon dioxide emissions would have been 28% lower and tax revenues higher by 3.8% of global GDP. Similarly, a study of US oil industry found that at low oil prices of US$ 50 per barrel, around half of not-yet-developed oil fields, equivalent to 6 billion tonnes of CO_2, are dependent on subsidies to breakeven (Erickson et al. 2017). However, another study claims that in a low oil price scenario, removal of fossil fuel subsidies will have marginal impact on climate change where the subsidy removal would reduce the carbon price required to stabilize GHG concentrations at 550 ppm by only 2-12% (Jewell et al. 2018). On the other hand, a review of subsidy reform in 25 countries in past 60 years suggests that such reforms can bring positive outcome for energy prices and national economic development in their respective countries (Sovacool 2017).

In 2009, the group of 20 economies (G-20), representing 96% of global coal and 83% global oil consumption, signed an agreement to phase out fossil fuel subsidies in their respective countries. The G-20 has also agreed to monitor the subsidy reforms in each country through peer review and third-party independent assessments (Aldy 2017; Rentschler and Bazilian 2017). Some of the G-20 countries have used the opportunity of low oil prices to implementing the subsidy reforms (Jewell et al. 2018).

[BOX 6.4 ENDS HERE]

6.4 Mitigation Options

This section describes mitigation options in energy supply, energy transformation, energy transportation, and from an energy systemic perspective. Mitigation options in land use and energy demand are addressed in other chapters of this report, although they are touched on here to the extent that there is overlap with the topics of this section. This section assesses the answers to three motivating questions. First, what are the key current and possible energy sector mitigation options? Second, what are the characteristics of these technologies that are relevant for assessing potential future energy system transformations? Third, what is the status and future prospects for these options?

6.4.1 Elements of Characterization

There are many ways to characterize 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 characterize the potential role of mitigation options. Mitigation is tightly linked with other societal priorities, including, the sustainable development goals that address 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 economic costs. Other factors may inhibit and enable the implementation of mitigation options. Assessment of mitigation options must therefore extend beyond cost and technological characterizations and touch on a broader range of issues relevant to their use.

This section characterizes different options and technologies considering six dimensions: geophysical, environmental-ecological, technological, economic, socio-cultural, and institutional (see Chapter 1).

Table 6.4 Dimensions and criteria to assess the barriers and enablers of implementing options and technologies in low carbon energy systems.

Metric	Indicators
Geophysical: Are the required resources available?	• Physical potential • Geophysical resources (e.g. resource depletion of minerals and fossil) • Land use • Geological storage capacity
Environmental-ecological: What are the wider environmental and ecological impacts of the options and technologies?	• Air pollution • Toxic waste • Ecotoxicity and eutrophication • Clean water • Biodiversity
Technological: Can the required technology be upscaled soon?	• Learning curve of technologies • Technology diffusion (scalability, maturity) • Integration in land-energy systems
Economic: What economic conditions can support or inhibit the implementation of the options and technologies?	• Costs in 2030 and in the long term • Investment needs • Employment effects • Effects on economic growth (including productivity enhancement) • Compatibility with current markets and business models • Effects on energy and food prices
Socio-cultural: What conditions could support or inhibit acceptability, adoption and use of the options and technologies?	• Public acceptability of options and technologies • Likelihood of required behavior change • Effects on health and wellbeing • Energy accessibility and security (including affordability) • Water accessibility and affordability • Poverty reduction • Food security (including affordability) • Equity and justice (across groups, regions, generations)
Institutional: What institutional conditions could support or inhibit the implementation of the option and technologies?	• Political acceptability • Institutional capacity and governance (including cross-sectoral coordination of policies and actions) • Agency, power and structures

6.4.2 Energy Sources and Energy Conversion

This subsection discusses the character of energy sources and energy conversion technologies. As countries explore options for climate mitigation, an important factor is that countries are endowed with different energy resources, leading to potentially different options for mitigation.

[Placeholder-We are considering creating a figure with some assessment of resources by region that might be a nice guide for the rest of this section. What is below is a placeholder on renewable energy percentages, which is different than what we might ultimately intend to include.]

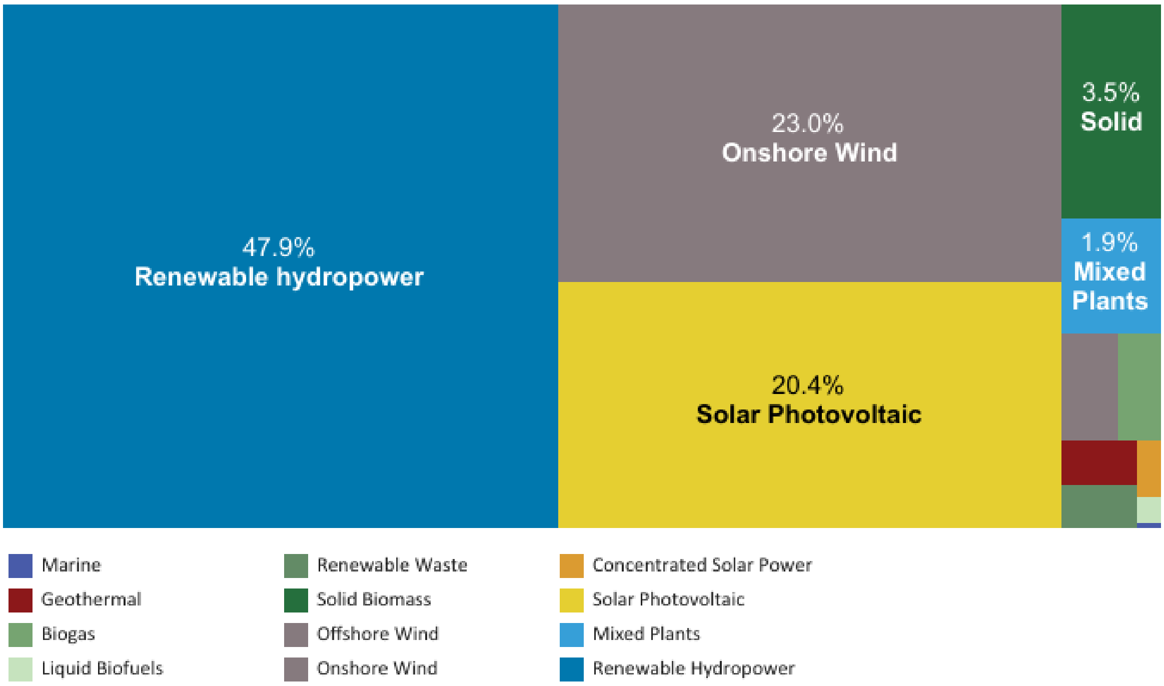


Figure 6.12 Installed renewable energy in 2018 by technology. Source: IRENA (2019).

6.4.2.1 *Solar Energy*

[Geophysical] Solar energy is by far the most abundant energy resource on Earth and is ubiquitous over the Earth's surface. More energy from sunlight strikes Earth in 1 hour than all of the energy consumed by humans in an entire year (Lewis 2007). The geophysical solar resource can be represented as global horizontal irradiation (GHI) important for flat-plate PV technologies and direct normal irradiation (DNI) important for CSP and CSV technologies. Unsurprisingly, areas closer to the equator have greater annual potential, reaching over 7 kWh/m^2 per day in desert regions of the world. There are 6 major GHI hotspots (western South America; northern, eastern and southwestern Africa; the Arabian Peninsula and Australia), with annual averages of > 2200 kWh/m^2 (Prăvălie et al. 2019). Geographical variations are due to position with relation to the equator, clouds, aerosol concentration, water vapor content, and ozone. While solar tracking systems exist to reduce the impact of geographical variations, these can only harvest direct sunlight, which is most affected by weather variability.

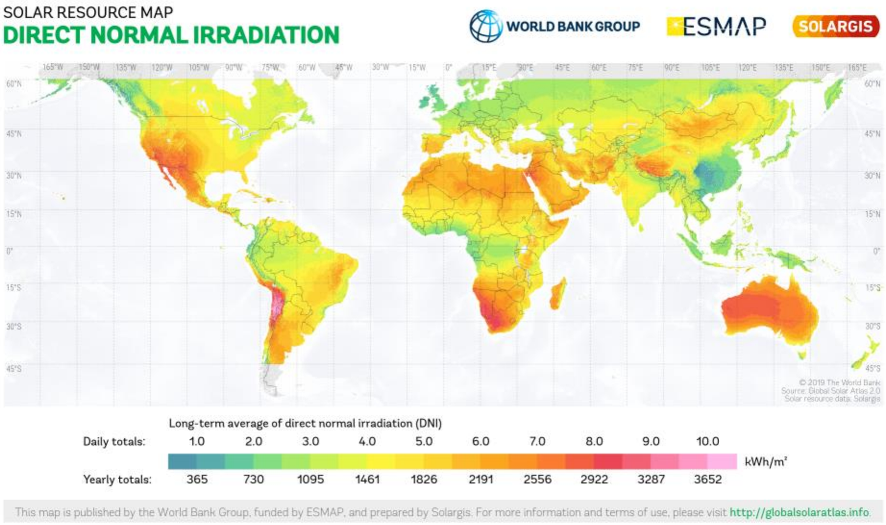


Figure 6.13 Global distribution of the annual mean direct normal irradiation (DNI, kWh/m^2). Source: Global solar atlas (2019).

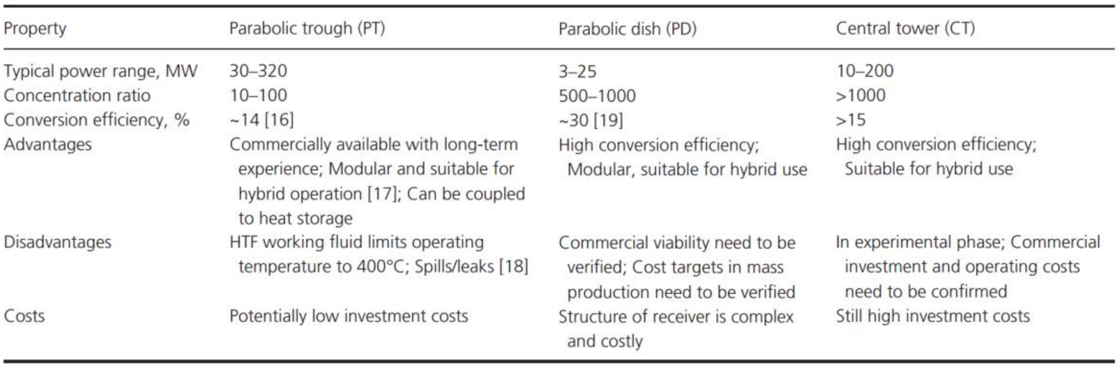
[Technological] The current dominant technologies are solar photovoltaics (PV) and, to a much lesser extent, concentrating solar power. PVs convert sunlight directly into electricity. Concentrating technologies use reflective surfaces, such as parabolic mirrors to concentrate sunlight to a receiver (CPV) or heat a receiver (CSP), which subsequently transforms heat into electricity via a thermoelectric power system. Solar heating and cooling are also well established technologies, and solar energy can be utilized directly for domestic and/or commercial applications such as drying, heating, cooling, cooking, etc. Solar energy can also be used to produce solar fuels, for example, hydrogen or synthetic gas (syngas).

Enhancing the technical potential for PVs would require improvement in conversion efficiency of the current solar cells. The most important development in this domain is the development of perovskite cells (Petrus et al. 2017). Apart from the fundamental scientific challenges such as these, it may also be pragmatic to rely on smart system integration.

CSP can deliver large-scale power plants (up to 300 MW). One advantage of CSP is its scalability. Another is storage. CSP plants can be constructed to maintain substantial thermal storage, which is valuable for load balancing over the diurnal cycle. Moreover, as with PV, CSP is also known to have significant societal advantages such as the prospects of large employability of workers (Islam et al. 2018). However, unlike PV, only strong direct sunlight can be concentrated for electricity generation. CSP requires therefore high level of direct normal irradiance (DNI) which constraints the cost-effectiveness of CSP deployment to a limited number of regions (Figure 6.3). Regions suitable for CSP include North Africa, Middle East, Southern Africa, Australia, the Western United States and parts of South America (Mexico, Peru, Chile) the Western Part of China and Australia (IEA, 2010 IRENA, 2012). Indeed, the current installed CSP capacity is mainly located in these regions. Other areas that might be suitable include the extreme south of Europe and Turkey, other southern US locations, central Asian countries, places in Brazil and Argentina, and other parts of China (IEA, 2010).

Parabolic through (PT), central tower and parabolic dish are the three main solar thermal technologies currently deployed. The technical performance and viability of three technologies have been demonstrated, (Wang et al. 2017d). Parabolic through and, to a much lesser extent, central tower are commercially the most mature technologies. PT represented approximately 70% of new capacity in 2018 with the balance made up by central tower plants (REN21, 2019).

Table 6.5 Key characteristics of solar thermal technologies (Source (Wang et al. 2017d)).



Property	Parabolic trough (PT)	Parabolic dish (PD)	Central tower (CT)
Typical power range, MW	30–320	3–25	10–200
Concentration ratio	10–100	500–1000	>1000
Conversion efficiency, %	~14 [16]	~30 [19]	>15
Advantages	Commercially available with long-term experience; Modular and suitable for hybrid operation [17]; Can be coupled to heat storage	High conversion efficiency; Modular, suitable for hybrid use	High conversion efficiency; Suitable for hybrid use
Disadvantages	HTF working fluid limits operating temperature to 400°C; Spills/leaks [18]	Commercial viability need to be verified; Cost targets in mass production need to be verified	In experimental phase; Commercial investment and operating costs need to be confirmed
Costs	Potentially low investment costs	Structure of receiver is complex and costly	Still high investment costs

[Economic] From an economic perspective, solar PV combines two advantages. On the one hand, module manufacturing can be done in large plants, which allows for economies of scale. On the other hand, PV is a very modular technology that can be deployed in very small quantities at a time (IEA 2018). However, solar energy is intermittent by nature and has low efficiency in terms of terms of sunlight-to-electricity conversion (10-20% in most cases). However, when using newer materials such as GaAs (Gallium Arsenide), solar cell efficiency had achieved a 40% at the end of 2010 (Kumar Sahu 2015). Large scale installations can also be a problem due to the removal of large areas of land use – between 4 and 6 acres for 1 MW of solar electricity production (Kabir et al. 2018).

The cost of solar PV installations can roughly be divided into two components: the modules, and balance of system (BOS) items such as the support structure, inverters, and the cost of installation. Driven by an 81% decrease in solar PV module prices since the end of 2009, along with reductions in BOS costs, the global weighted average levelized cost of electricity (LCOE) of utility-scale solar PV fell 73% between 2010 and 2017, to 0.10 $/kWh. Rapid declines in installed costs and increased capacity factors have improved the economic competitiveness of solar PV around the world.

Though solar PV technology has been gradually matured, large differences of regional cost persist. Different domestic market maturity levels, as well as differences in local labor and manufacturing costs and different policy environment can all influence its competitiveness. The following figure shows the total installed cost of commercial solar PV and levelized cost of electricity by country or state during 2009-2017. The lowest average total installed costs for commercial PV can be found in Germany and China, at 1100$/kW and 1150$/kW, respectively. The highest cost market remains in California with total installed costs of 3,650$/kW. In terms of the LCOE of commercial solar PV, the lowest average LCOE was around 0.10$/kWh in Australia in 2017 (IRENA, 2018).

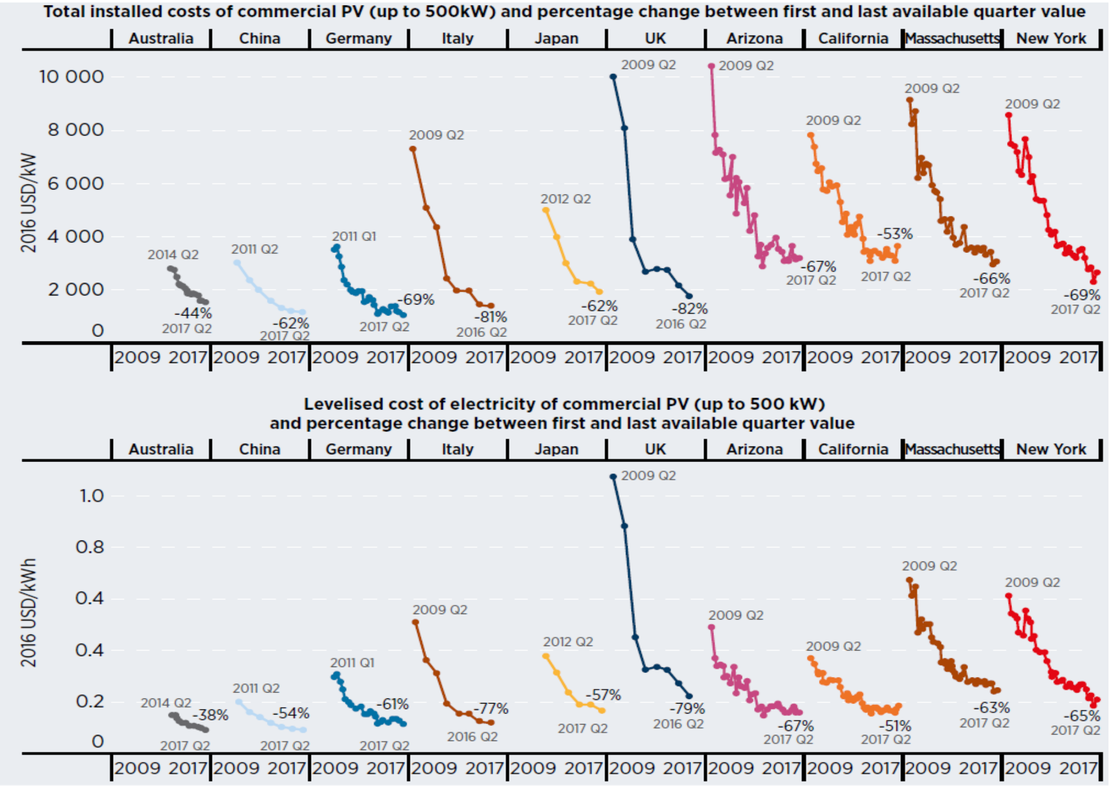


Figure 6.14 ***Total installed costs of commercial PV (up to 500kW) and percentage change between first and last available quarter value*** **Source: IRENA Renewable Cost Database**

While rapid deployment has driven substantial cost reductions over the past decade, technology improvements are likely to return as a major factor behind future reductions, together with the increasing market maturity reducing financing costs.

Demarcation of costs of solar generation may be inferred in various ways and therefore it is valuable to properly note assumptions and metrics when reporting such costs. First, the costs of solar modules themselves have been reporting to be falling in the past two decades. On the other hand, extraneous factors may result in some increases as well (see Table 6.). Because solar is a capital-intensive technology, several numbers have been reported by operators as well as laboratories. As such, domestic systems are benchmarked at $ 2.7/Wdc and commercial systems at $ 1.7/Wdc. The cost reductions so far have broadly been due to reductions in the cost of solar modules (Fu et al. 2018). Mechanisms for solar PV cost reductions are broadly through lower-level changes such as cost of materials and increased efficiency, and higher-level changes such as economies-of-scale have also been observed (Kavlak et al. 2018).

Numerous governmental initiatives have aimed at reducing PV prices especially in the developing world. Thus, it is also important to consider the costs without subsidies especially as several regions have seen a massive uptake of residential PV due to financial benefits. Research from the US indicates that PV may still not have achieved socket parity in the absence of subsidies and only 3% of the US demonstrates the ability to have cost-competitive PV without subsidies (Hagerman et al, 2019). This indicates the need for continued financing of PV prospects, which may have even larger benefits in the developing countries (Ondraczek et al, 2015).

Table 6.6 Drivers of cost increase and decrease in residential, commercial and utility-scale PV (Fu et al. 2018).

Sector	Residential	Commercial	Utility-scale
Decrease	• Higher module efficiency • Lower structural BOS commodity price • Lower electrical BOS commodity price • Higher labour productivity • Lower supply chain costs • Decrease in higher-cost module inventory. Higher small installer market share • Lower permitting cost	• Lower inverter price • Higher module efficiency • Smaller developer team • Lower permitting and interconnection costs	• Lower inverter price • Higher module efficiency • Optimized design coefficients for wind loads • 1,500 Vdc to replace 1,000 Vdc • Lower developer overhead
Increase	• Higher mixed inverter price due to higher advanced inverter adoption • Higher module price • Higher labour wages	• Higher module price • Higher labour wages	• Higher module price • Higher labour wages • Higher steel prices

Apart from the direct costs themselves, there are also other costs associated with solar PV since the technology has not been able to provide ample baseload supply. First, the costs of integration are estimated to be high – up to 50% of total costs in scenarios with high penetration (Hirth et al. 2015). A significant amount of these costs is associated with low utilization of the capital. Similarly, a notable issue with solar PV is that excess generation in particular regions might result in the need to curtail available generation. These costs, while highly variable can again be very significant and as high as $ 80/MWh when solar energy penetration exceeds one-fourth of the total generation capacity (Denholm et al, 2015). To control such curtailment to minimum possible levels, electricity storage technologies are required. Such technologies currently cost at least $ 250/MWh but may be anticipated to reduce by ~50% by mid-century at which levels, solar PV with storage may have high deployment (Schmidt et al, 2019; Lai and McCulloch, 2017).

[Environmental/Ecological] Distributed and utility-scale solar energy (USSE) installations integrated into the existing built environment (e.g., roof-top PVs) will likely have negligible direct effects that adversely impact biodiversity (Hernandez et al. 2014). The main environmental concern with large PV power plants is in the conversion of large swaths of space or land be used to collect and concentrate solar energy (Hernandez et al. 2015). There the aboveground vegetation is cleared, and soils typically graded, and regionally by landscape fragmentation that create barriers to the movement of species. In addition, water is required for panel washing and dust suppression, and environmental toxicants are often required for USSE operation (e.g., dust suppressants, rust inhibitors, antifreeze agents) and herbicides may have insalubrious, and potentially long-term, consequences on both local and regional biodiversity (Hernandez et al. 2015). In the case of CSP, the water consumption depends on the cooling system adopted—wet cooling, dry cooling, or a combination of the two.

As with the development of any large-scale industrial facility, the construction of USSE power plants can pose hazards to air quality, the health of plant employees, and the public. During the decommissioning phase, PV cells can be recycled to prevent environmental contamination due to toxic materials contained within the cell. On rooftops, solar PV panels have also been shown to reduce roof heat flux, conferring energy savings and increases in human comfort from cooling.

[Socio-Cultural] Besides the advantages of utilizing the sun as a renewable source of electrons and heat, and the reduction of air and water pollution by fossil fuels, additional environmental co-benefit opportunities activities exist. These include (1) utilization of degraded lands, (2) co-location of solar panels with agriculture, (3) hybrid power systems, (4) floatovoltaics, and (5) novel panel architecture and design that serves to concomitantly conserve water and land resources (Hernandez et al. 2014).

[Institutional] Financial incentives have had a major impact on solar deployment. Solar costs have dropped dramatically in recent years. Both the United States and Europe have observed capacity growth due to cash rebates, tax incentives, etc. in various countries/regions(Crago and Koegler 2018; Dusonchet and Telaretti 2015). Utilizing such incentives has successively lowered prices through technological learning and economies of scale, which in turn has reduced the costs of the technology itself. Thus, while learning rates for coal-fired power plants was 6-10, that for solar PV is 10-47% - implying rapid improvements in technological readiness due to commercialization (Rubin et al. 2015a).

Solar energy, through a variety of applications (e.g. rooftop solar), has the potential to meet as high as half of the global energy demands. Doing so requires regionally-appropriate identification of investment needs, technological improvements in conversion efficiency and utilization of near- and longer-term system “smart” integration approaches. Because of the vast resources, much of the solar resources that could be harnessed remains untapped. Advancing solar generation will require (i) enhancing potential in regions where solar generation has already begun and continuing such momentum and (ii) creating necessary social and financial condition so as to jumpstart deployment.

BOX 6.5 Solar Power - What’s New Since AR5

[Placeholder-This is a placeholder for the SOD, we will include a short summary of important changes since AR5.]

6.4.2.2 *Wind Energy*

[Geophysical] One estimate suggests that there is 1 million GW of wind energy available from the total land coverage of the Earth, and if only 1% of this land was utilized at achievable efficiencies this would meet global electricity demand. Without considering restrictive land use or environmental conditions, it is estimated that about 3% of the world’s land area has excellent wind resources (Bandoc et al. 2018). These potential hotspots exist on every continent (Figure 6.), but potential areas are larger in the Americas, Europe and Asia. Offshore wind power offers tremendous potential, because winds are stronger and steadier than over land, but exploitation is more expensive.

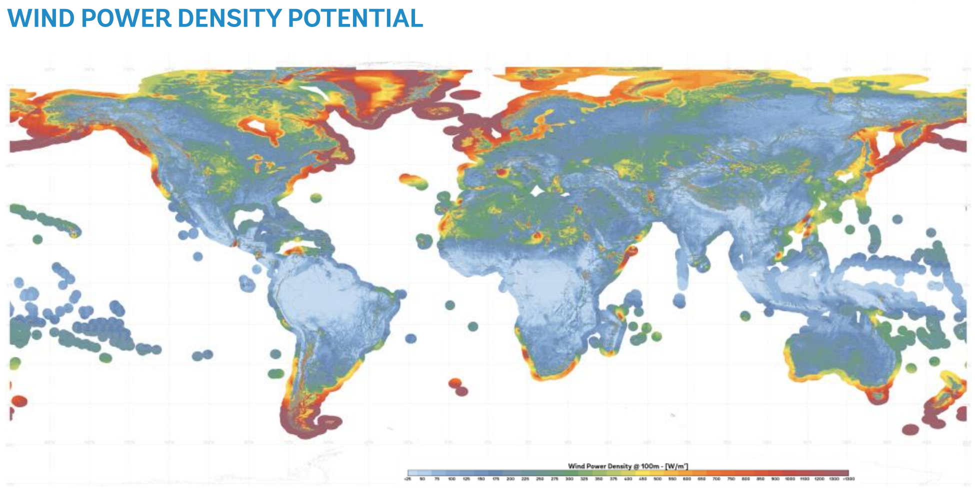


Figure 6.15 Wind power density potential

[Technological] The wind industry has evolved substantially since its utility-scale start in the late 1970s. In the late 1980s, wind turbines nominal capacities ranged from 30 to 70 kW. Nowadays, most current wind turbine models range from 3 MW to 7 MW, with 10-12 MW models in testing, and the wind energy industry is mainstream (Rohrig et al. 2019)(Rohrig et al. 2019). All major onshore wind markets have seen rapid growth in both rotor diameter and the capacity of turbines since 2010. In 2018, average turbine capacity ranged from 1.9 MW to 3.5 MW, and rotor diameter from 97 to 118 m. 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. The largest turbine in the world was installed in the United Kingdom in 2018, an 8.8 MW turbine with a rotor diameter of 164m.

Wind turbines have not only evolved 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)(Rohrig et al. 2019). A clear trend to higher capacity factors for new offshore European wind farms can be seen since 2008, with average capacity factors rising from an average of around 38% to around 47% in 2017 and 43% in 2018 (IRENA 2019c). Driven by these technology improvements, global weighted-average capacity factors have improved substantially for onshore and offshore wind between 1983 and 2018. The average capacity factors for newly commissioned onshore wind farms in 2018 in Denmark, Germany, Sweden and the United States were 40% to 129% higher than onshore wind farms commissioned in 1984. And more recently, in Denmark, their average capacity factor grew by almost half, from 27% in 2010 to 39% in 2018.

From one hand, developments in wind turbine control, including variable speed control, reduce fatigue and limit loads on the wind turbine structure in certain situations. On the other hand, there is 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 stabilization of the grid, thereby allowing for higher penetration of wind power in the existing power grids (Rohrig et al. 2019).

[Economic] The global weighted-average installed costs of onshore wind have declined by 71% in 35 years, from around USD 5,000/kW in 1983 to USD 1,500/kW in 2018. In the last decade, data from the International Renewable Energy Agency (IRENA) in Figure 6.16 shows that the global weighted average total installed cost has decreased from 1,913 USD/kW in 2010 to 1,497 2018 USD/kW. The fall in prices is mainly driven by declines in wind turbine prices and balance of project costs. Wind turbine costs have fallen by between 44% and 64% since their peak in 2007–2010, depending on the market. Chinese wind turbine prices have fallen by 78% since 1998 but have been broadly flat since 2015. The most recent data shows average turbine prices around USD 500/kW in China and USD 855/kW elsewhere. Reductions in total installed costs vary by country and when large-scale commercial deployment starts. China, India and the United States 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. The total installed costs for onshore wind projects are very site- and market-specific. For projects commissioned in 2018, the range between the lowest and the highest installed cost was significant for onshore wind in most regions, except for China and India. The average installed costs range from USD 1,170/kW in China to USD 2,237/kW in Asia (IRENA 2019c).

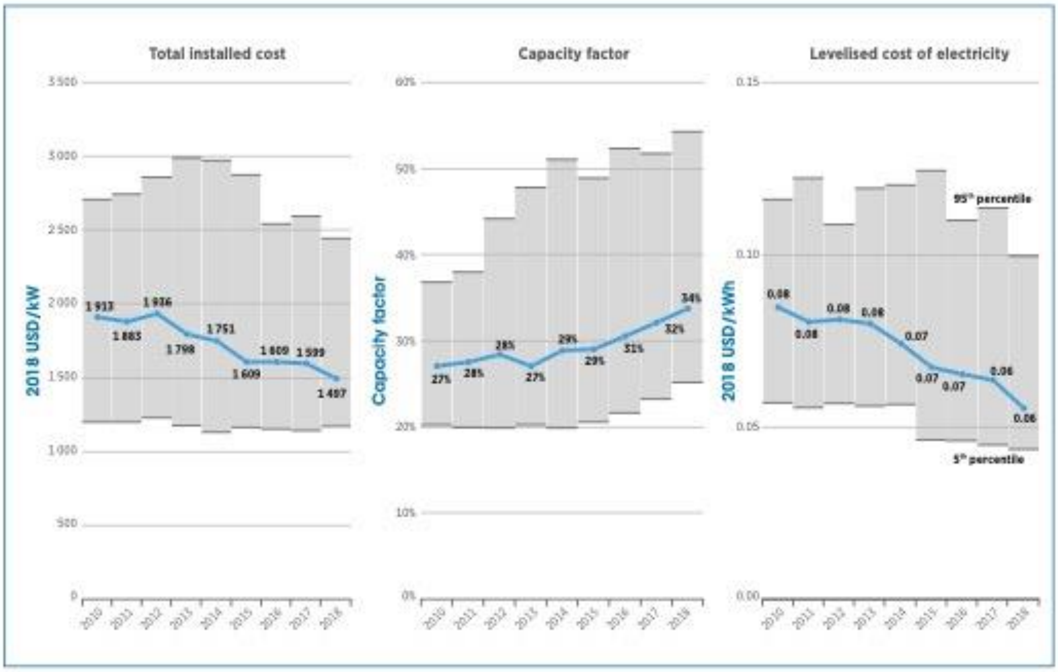


Figure 6.16 Global weighted average total installed costs, capacity factors and LCOE for onshore wind, 2010–2018. Source: (IRENA 2019d)**.**

In 2018, globally weighted-average levelized cost of electricity (LCOE) from onshore and offshore wind projects have all been within the range of fossil fuel-fired power generation costs (IRENA 2019c). The global weighted-average LCOE for onshore wind fell by 82% between 1983 and 2018, over which time cumulative installed capacity grew to 540 GW. The average LCOE of newly commissioned onshore wind farms in Denmark, Germany, Sweden and the United States were 69% to 83% lower in 2018 than for those commissioned in 1983. The United States and China both had country average LCOEs of USD 0.05/kWh, while Brazil, Canada, Denmark, India and the United Kingdom all averaged USD 0.06/kWh in 2018. The country or regional weighted-average LCOE was between USD 0.05 and USD 0.07/kWh in 2018, except in Asia. The weighted-average LCOE of new projects in 2018 in China, North America and South America (excluding Brazil) was USD 0.05/kWh (IRENA 2019c).

New offshore wind projects have moved to deeper waters and further offshore (IRENA 2019c). Projects in recent years have typically been built at water depths between 10 m and 55 m and up to 90 km offshore, compared to around 10 m water-depth in 2001–2006, when distances to port 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. A newer emerging technology makes use of wind turbines installed on floating structures (Watson et al 2019), which could operate in deep waters. The first floating wind farm in Scotland was erected in 2018. This type of technology is particularly important for regions like the USA West coast and the east coast of Japan where the waters near the coast are too deep for conventional offshore wind farms. The global weighted-average LCOE of offshore wind projects commissioned in 2018 was USD 0.127/kWh (IRENA 2019c). Like total installed costs, the average LCOE increased up to around 2011, before declining noticeably between 2016 and 2018. The weighted average LCOE was around USD 0.134/kWh in Europe in 2018. This was 28% higher than in China, where the value was around USD 0.105/kWh.

[Environmental/Ecological] In specific situations, wind power developments have been shown to cause environmental 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 technological development or the proper location of the wind farms. Many countries now require environmental studies of impacts of wind turbines on wildlife prior to project development. In a comprehensive recent series of articles (Poulsen et al. 2018), the impacts of wind farm noise on long-term human health have been shown to be well below detectable levels.

[Socio-Cultural] In a more general perspective, wind turbines can cause noise and aesthetic pollution, which challenges public acceptance. Understanding the complex elements of public acceptance of wind (and other renewable technologies) is closely related to a variety of local siting and planning approaches and host community stakeholder and engagement strategies (Aitken 2010a; Dietz and Stern 2008). There can be national support for renewable energy, yet local communities may not support the deployment of wind energy in their local area (Bell et al. 2005; Batel and Devine-Wright 2015). And these strategies and responses may vary site-by-site depending on the physical, environmental, cultural and social parameters of that site and whether the wind is deployed on land or offshore.

These approaches may pose complex responses that are related to public perceptions (Pidgeon and Demski 2012; Slovic 2000), place attachment, (Devine-Wright 2005, 2013), risk characterization and communication (NRC, Understanding Risk: Forming Decisions in a Democratic Society, 1996), and decision making processes fairness, and distributive justice (Firestone et al. 2012, 2018).

[Institutional] Despite current advances in technology and reduction in costs, wind energy faces important challenges. The Office of Energy Efficiency and Renewable Energies (2017), points out the many challenges of wind power development in the USA. There, wind energy must still compete with conventional sources, on a cost basis. Despite the fact that the cost of energy has decreased in the last ten years, the technology requires an initial investment larger than fossil fuel generators. The problem of energy storage is the last, but an important link to fully integrate weather-dependent renewables into society.

The WWEA Policy Paper Series (Identifying success factors for wind power, 2018) analyses the cases of Germany, Denmark, the Netherlands as well as Spain and the United Kingdom in wind energy to identify positive and negative experiences in specific areas. Notwithstanding the current trend towards auctions, the by far largest proportion of the installed wind turbines were installed under feed-in tariff legislation. Reports indicate that this instrument has been in particular useful as it has opened the market for all type of investors and that in particular SMEs and community-based investors took the chance and invested heavily in a new market. Experience in the United Kingdom, the Netherlands and more recently in Denmark do also show that a lack of local investors has a deep impact on the social acceptance of wind farms.

BOX6.6 Wind Power - What's New Since AR5

[Placeholder-This is a placeholder for the SOD, we will include a short summary of important changes since AR5.]

6.4.2.3 *Hydroelectric Power*

[Geophysical] It has been estimated that there is a global gross theoretical available potential of 36 to 128 PWh/year. Based on slope and discharge of each river in the world, a recent study (Hoes et al. 2017) estimates the gross theoretical hydropower potential is approximately 52 PWh/year divided over 11.8 million locations. This 52 PWh/year is equal to 33% of the global annually required energy, while the present energy production by hydropower plants is just 3% of the annually required energy. Previous studies(Zhou et al. 2015) estimated a much larger value of 128 PWh/year. Hydropower shows a significant potential for renewable energy in the future energy mix, although many of the locations cannot be developed for (current) technical or economic reasons. The greatest contributor to the hydropower potential is Asia (48%), followed by S. America (19%). Hydropower has a technical potential of approximately 8 to 26 PWh/year, and an economically feasible potential of 8 to 21 PWh/year (Zhou et al. 2015; Van Vliet et al. 2016b).According to the World Energy Council, there may be an available potential of hydroelectric generation worldwide of 10,000 TWh / year. This represents approximately 40% of the total energy generated during 2017.

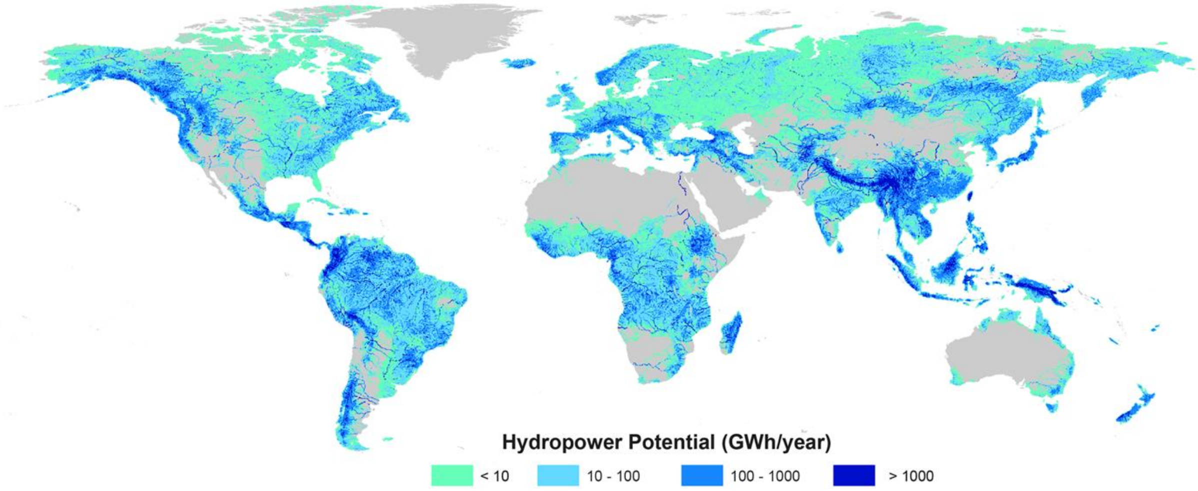


Figure 6.17 Global map of gross hydropower potential distribution, Source: Hoes et al (2017). |

[Technological] Hydroelectric power comes from water in motion, which turns turbines that convert the water's kinetic energy into electricity via a turbine shaft and a generator. Water constantly moves through the hydrologic cycle, which is ultimately driven by solar energy (through the evaporation of water). Hydropower plants can be located on rivers, streams and canals, but dams are needed for reliable water supply. Electricity from hydropower can be generated in three main ways: impoundment, diversion and run-of-river. Impoundment projects use a dam to store water, which is released to generate electricity among other water use demands. The water in the dam is replenished by natural sources or recycled by pumping it back up to a higher reservoir in order to be released again. This last method has the potential to be a form of storage for other RE sources. Diversion projects use a channel to portion the water from a river. Run-of-river projects use the flow of water within the natural range of the river (Sommers 2004).

The power range of a hydroelectric plant ranges from a few MWs to several GWs, which expands the possibilities of use and can be installed in regions with low demands or with very high demands. The efficiency of hydroelectric plants is greater than 85%; the highest of all generation technologies. Due to the high efficiency of hydroelectric technology, the excesses of electricity generation can be used to pump water to the reservoir in order to be able to use the water later at times with greater demand. Hydroelectric technology has the added advantage to allow high levels of penetration of intermittent renewable energy such as solar and wind energy to be achieved without compromising the reliability and continuity of the electricity grid, since it has the capacity to deal with the random variations in the power of intermittent power plants and it can be used as a peak load to reduce the costs derived from the dispatch of the most expensive plants.

[Economic] The investment cost for the hydroelectric plants involves the infrastructure that the plant requires for its operation such as: the curtain of the dam, the mechanical and electrical components, the connection to the transmission network, the creation of the dam, the cost of the site, the labor required for the planning and construction of the installation, etc. The cost of operation and maintenance includes a fixed cost and a variable cost. The fixed cost is derived from all those activities, which, no matter how much the plant operates during the year, will continue to have a cost, for example: workers' salaries, scheduled maintenance, etc. On the other hand, the variable costs are strictly related to the operation of the plant such as: the cost of turbined water, corrective maintenance or change of equipment, auxiliary materials for the correct operation of the equipment, etc. The cost of fuel for hydroelectric plants is the cost per m3 of water that is turbined for electricity generation, one of the cheapest in terms of cost per MWh during its operating time. However, this cost is relatively low with respect to the cost of fossil fuels, which is why it is sometimes considered non-existent. In addition, in some cases fuel costs are included in the cost of variable O & M.

[Environmental/Ecological and Sociocultural] Although hydroelectric power plants have many advantages over other energy sources, they also have potentially serious environmental and societal impacts. Hydropower dams and channels are obstacles for fish migration and often involve large modification of aquatic habitats.

Below the hydropower dam, there are considerable alterations to vegetation, natural river flows, retention of sediments and nutrients, and alterations to water quality and temperature. From a societal perspective, construction of power plants may lead to resettlement and may restrict navigation and affect outdoor recreation and fishery. In addition, management of competing water uses is needed.

Hydroelectric power generation is a technology that uses the potential and kinetic energy of water, so it does not emit any kind of greenhouse gases during the process of generating electricity, and it helps to control the frequency and the demand-generation balance; by not involving a thermal process it does not require a preheating for a fast and safe increase in power. Hydroelectric plants can be slow to finance and construct, but their lifetime is usually 60 years or more.

Because the water potential can be located in places with human settlements and hydroelectric plants are usually large projects, they do not have a social acceptance like other technologies. In addition, because large areas of land are flooded, the organic matter at the bottom of the dam can generate significant greenhouse gas emissions.

[Institutional] The construction time of hydroelectric power plants is longer than other 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). However, competition for hydropower across country borders could also be a forcing for conflict, especially under climate change impact in water resources (Ito et al 2016).

BOX 6.7 Hydroelectric Power - What's New Since AR5

[Placeholder-This is a placeholder for the SOD, we will include a short summary of important changes since AR5.]

6.4.2.4 *Nuclear Energy*

[Geophysical] 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 sufficient for over 130 years of supply as compared to 100 remaining years estimated in 2009. Overall, there is a 21% increase in identified uranium resources recoverable at a cost of less than USD 260 / kgU between 2009 and 2016: from 6.3 MtU to 7.99 MtU (NEA 2010; IAEA 2019c). If prognosticated and speculative resources are to be included, the conventional resource base rises to a total of about 15.5 MtU, extending the supply to nearly 250 years at current generation levels of nuclear power. In addition, conventional uranium resources are widely distributed around the world reducing the risks related to geopolitical factors. Furthermore, uranium is only one of the types of material that can be used to fuel nuclear reactors. Thorium, which is roughly four times as abundant in the earth's crust as uranium, is another alternative. Nevertheless, with a better understanding of uranium deposits and their ample availability, the interest in thorium-based fuel cycles has waned. Similarly, low uranium prices undermine the reprocessing option of the unused fissile material in spent fuel which could reduce substantially the requirements for uranium.

Nuclear energy would be practically decoupled from the resource constraint in case of a large-scale deployment of fully closed nuclear fuel cycles in the future. Fast Breeder Reactors (FBR) allow the extraction of over 50 times more energy per kg of uranium with corresponding reductions for mining and enrichment, and generation and disposal of high-level radioactive waste. However, as a result of subsequent discoveries of uranium resources around the globe and nuclear capacities growing at a much slower rate than previously estimated, an adequate supply of uranium ore and reliable fuel supply to the market weakened the incentives for swift development of FBRs.

[Technological] Pressurized water reactors (PWRs) constitute most of the world's existing nuclear power plants and plants under construction (IAEA 2019a). Some of the PWRs (Generation III / III+) under construction include evolutionary and advanced reactors designs such as the AP1000 (in the U.S.), VVER-

1200 (in Russia, Belarus, Turkey and Bangladesh), EPR (in Finland, France and UK), HPR1000 (in China and Pakistan), and APR-1400 (in South Korea and United Arab Emirates). Key characteristics of these reactors are improved fuel technology, superior thermal efficiency and significantly enhanced safety systems (including passive nuclear safety).

While currently available large-scale reactors of Generation III and III+ are the main option for near term deployment, there's a substantial effort invested into research and development of advanced nuclear technologies including Small Modular Reactors (SMRs). SMRs are still not commercially available and another decade might be needed before larger scale orders are expected. There are around 50 SMRs designs at different stages of consideration and development, from conceptual phase to licensing and construction of first of a kind facility (IAEA 2019b). The most advanced projects rely on light-water-cooled technology and have reached advanced licensing stages or are under construction. SMRs are expected to offer lower overall investment (units of less than 300 MW per module) and easier financing, while modularity and off-site pre-production should allow greater efficiency in construction, shorter delivery times and overall cost optimization (IEA 2019c). Smaller unit sizes would allow owners and operators to optimize their generation portfolio, offer flexibility in construction and operation, and enable integration into smaller grids and areas with lower water availability, thus supporting risk diversification in changing electricity markets. SMRs designs incorporate advanced solutions related to safety (passive systems, less components and simplified designs) and waste management, require smaller emergency planning zones and simplified emergency preparedness procedures (easier siting), that could positively influence public acceptance and facilitate licensing. Most SMRs designs offer increased load following capability that makes them suitable to operate in smaller systems and in systems with relatively high shares of VRE. Their market development will strongly depend on the successful deployment of prototypes and first-of-a-kind plants.

Additional products could increase attractiveness of nuclear in some cases (e.g. provision of heat for thermal processes, hydrogen production, desalination). Funding through the public and private research and development channels and standardization of designs are crucial to achieve fast technological progress, early deployment and eventual use at larger scales that would allow cost competition with other options and overcoming the burden of initially high investments.

[Economic] Nuclear power plants have a front-loaded cost structure; they are relatively expensive to build but relatively inexpensive to operate. Because of the sheer scale of the investment required (projects can exceed US $10 billion in value), nearly 90% of nuclear power plants under construction are owned by state-owned companies with governments assuming most of the risks and costs. Sustained favorable political and financial framework conditions are crucial for new nuclear builds.

In the absence of adequate political support, financing is often a major hurdle to project development. Risks may occur at all stages of the project life cycle, but given the importance of up-front capital costs, risks that can lead to cost overruns and delays during the construction phase are of particular concern. Lower than expected revenues during the operating phase (e.g. volatile electricity prices in competitive markets, lack of stable and strong carbon pricing) is another key concern affecting the economics of nuclear power. Market conditions have been cited as the main reason for early shutdowns of several nuclear power plants in the U.S., along with increased regulatory and safety requirements rendering some plants financially unviable (IEA 2019c).

Transformation of electricity markets, in particular increasing shares of variable renewable energy sources and low natural gas prices have dampened electricity prices in many markets, creating a challenging environment for other generators, including nuclear energy. In addition, costs associated with the integration of higher shares of VRE sources—including the cost associated with increased transmission and distribution capacity requirements and the costs associated with providing additional short term balancing (provision of flexibility) and long-term firm capacity—are not properly allocated in most markets, creating inefficiencies in the transition to low carbon electricity systems. Similarly, the value of services such as capacity availability (e.g. capacity mechanisms) and load following are not adequately remunerated. Nuclear power plants have the technical potential to provide these services by operating in a flexible manner with minor additional investments (e.g. in France, Germany). Nevertheless, less hours in operation will have a significant effect on the revenues (as compared to the baseload operation) and should be reflected in the remuneration of flexibility service.

[Environmental/Ecological] As a dispatchable low carbon technology, nuclear power can contribute to climate change mitigation as well as to system reliability, adequacy and energy security. However, the value of these and other environmental and social benefits is not reflected in government policies. On a life cycle basis, nuclear power is among technologies with the lowest acidification and eutrophication potentials, thus having a very small impact on ecosystems compared to alternatives. Land use intensity of energy resources could be another important factor for some countries when transitioning to a clean energy system. Not only is the land footprint of a nuclear power plant, per unit of output, among the lowest across the power technologies, but also material requirements are low (e.g. aluminum, copper, iron, rare earth metals). When comparing the impact of different technology options on human health measured in disability adjusted life years (DALYs), nuclear power again has a relatively low impact along with solar, wind and hydro (IAEA 2016).

The transition to a more sustainable energy system is also an opportunity to stimulate economic activity, enhance employment and improve the well-being of citizens. A nuclear power project creates many long-term jobs in operations, contracting and in the supply chain. Also, a highly skilled labour force is necessary to design and operate complex nuclear technologies compared with other technologies, thus giving potential to enhance national human capital and generate economic value through spillover effects on related industries (IAEA 2009).

[Sociocultural] Irrespective of the sustainability benefits, the contribution of nuclear power to climate change mitigation and SDGs will ultimately be determined by political and public support. Public attitudes towards nuclear energy tend to fluctuate and differ across countries, notably in the immediate aftermath of accidents (e.g. Chernobyl, Fukushima). The general public has little direct experience with complex nuclear technologies, creating a situation where the benefits of nuclear power are unclear and risks can be exaggerated. To maintain and increase public support, decision makers need to better understand the factors governing perceptions of risk, provide tailored information, and ensure that transparent and participative processes lead to fair and consistent decision making (IAEA 2016, 2017). For example, a study in Sweden showed how extensive information programmes in four municipalities have positively changed the extent to which people accepted a local radioactive waste repository (Sjoberg 2004).

Public concerns about nuclear power are in many cases related to issues of safety, security, waste management and proliferation. While there has been a long term trend towards increasing safety in the nuclear industry, the Fukushima Daiichi accident in March 2011 prompted additional efforts. These include national, regional and international near term and long term actions, including the IAEA Action Plan on Nuclear Safety (2011), to evaluate and mitigate the safety vulnerabilities of nuclear power to external hazards (IAEA 2014). Nuclear power should be safe and used solely for peaceful purposes, supported through safeguards measures (including activities of the IAEA and others) to build confidence and foster and secure technical co-operation.

In particular public confidence could be improved with the opening of the first disposal facility for high level waste (HLW). Noteworthy to mention is that only 2–3% of the radioactive waste is HLW, which presents particular challenges in terms of radiotoxicity and long half-life; the remaining 97–98% is low and intermediate level waste for which disposal options are already being implemented in many countries. Regarding the HLW, scientific consensus is that the safety and isolation of the disposed HLW from the environment can be assured in stable geological formations combined with multiple engineered barriers. Nevertheless, progress towards opening HLW disposal facilities has been slow, and none is yet in operation. Finland and Sweden have made the greatest advances in this field. In November 2015, Finland granted Posiva, an expert organization in nuclear waste management, a construction license for Finland’s HLW disposal facility in Olkiluoto. In March 2011, the Swedish Nuclear Fuel and Waste Management Company applied for a construction license for Sweden’s disposal facility at Forsmark . Both facilities are intended to start operation in the 2020s.

[Institutional] The reasons behind current slow rates of deployment are numerous: (1) inadequate political support and overall public acceptance, mainly driven by various facility accidents in the past (e.g. Chernobyl and Fukushima); (2) very high initial costs and complex financing arrangements; (3) long lead times in project and infrastructure developments; (4) electricity market liberalization leading to increased insecurities in sales, volatile electricity prices, competition from other technologies and structural market deficiencies (e.g. system costs allocation, out-of-market payments to variable renewable energy sources (VRE)).

BOX 6.8 Nuclear Power - What's New Since AR5

[Placeholder-This is a placeholder for the SOD, we will include a short summary of important changes since AR5.]

6.4.2.5 *Carbon Dioxide Capture, Utilization, and Storage*

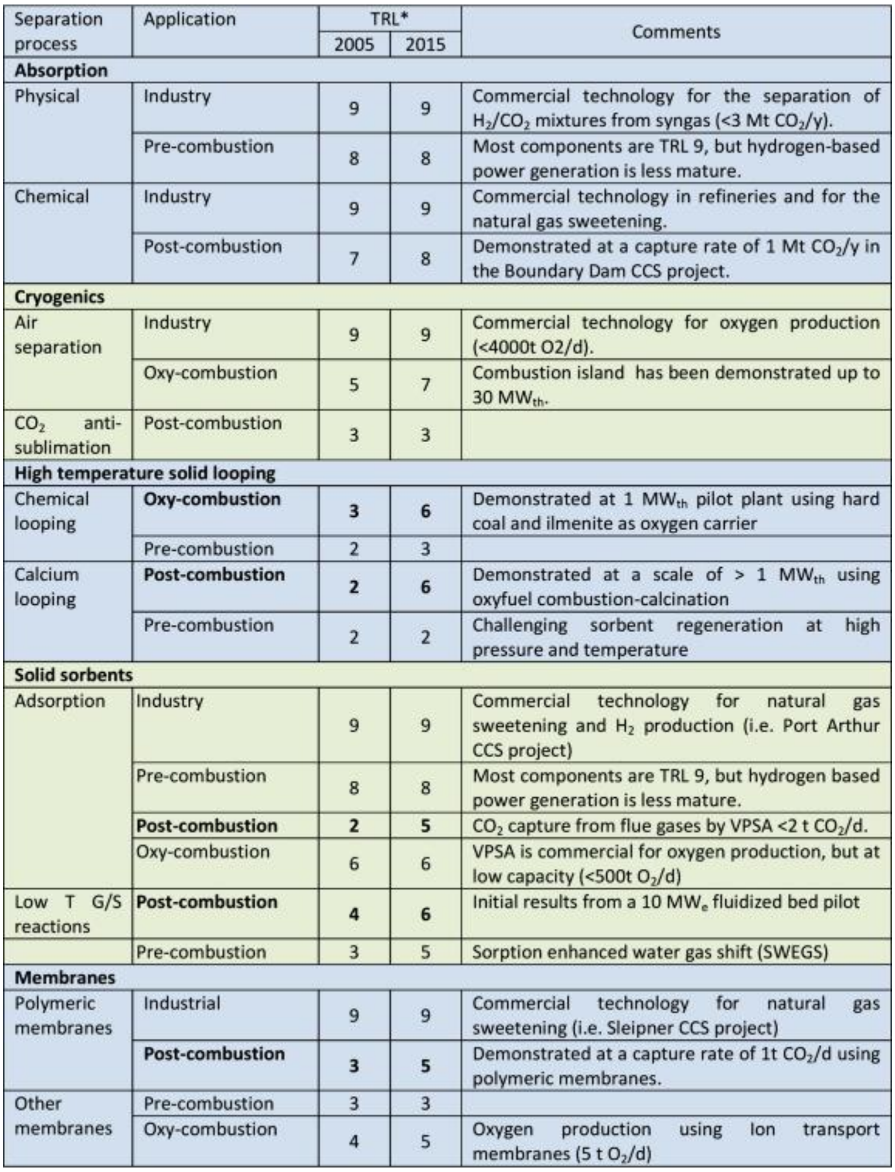
It has been noted in Section 6.7 of this chapter that continued fossil fuel usage will be influenced by the availability of CO_2 capture and storage (CCS). While the IPCC SRCCS provides detailed technological overview for this technology, we try to provide some newer developments in terms of costs and potential in this section. Here, CCS refers to CO_2 separation from the flue gas in fossil fuel power plants and a separate section is devoted to bioenergy with CCS (BECCS) to deliver negative emissions.

[Geophysical] The potential for CCS and its matching with the carbon mitigation requirement remains differentially estimated for different locations and thus, requires advanced understanding of source-sink mapping, geological and engineering considerations to limit down from the theoretical potential. Broadly, CCS potential hinges on total amount of CO_2 that is released, the energy efficiency of the separation process, proximity to geologic sinks (i.e. source-sink mapping) and suitability of the sink. Studies that have appeared in the last five years within various regions have tried to integrate all these and thus assimilate studies on individual domains. Understandably, these are extremely localized factors and accordingly, national studies focusing on individual countries and even regions have emerged. On one hand, IAM exercise help the scoping of CCS by estimating its share in an individual countries (see section 6.7.4). Bottom-up analyses can help augment this understanding by mapping the potential from regionalized contexts onto the overall mitigation potential. This can be done by comparing the literature that has appeared for various countries (for instance, see Zhu et al, 2015; Sun et al, 2018). Illustrative estimates are 30-200 Gt-CO_2 for China and 5-25 Gt-CO_2 from India from a developing country exercise carried out by Viebahn et al (2014; 2015).

[Technological] Technological configurations are likely to be used in ways that incentivize CCS costs earlier on in the process. Accordingly, most of the CCS literature cited earlier does show the significant advantage of utilizing enhanced oil recovery or enhanced gas recovery from conventional as well as unconventional formations (Edwards and Celia 2018); Bielicki et al, 2017). Having said that, such approaches are mostly location dependent and require considerable residual oil. Moreover, concerns have been echoed about the net carbon efficiency if the CCS process itself gives rise to large carbon emissions during refining and combustion (Cooney et al. 2015; Azzolina et al, 2016). Similarly, geographical circumstances determine the prospects of cost reduction – through economies-of-scale – by clustering together of several CO_2 sources wherein the cost advantages of ~\$10/t-CO_2 may be observed (Garg et al, 2017; Abotalib et al, 2016). Plant-level changes such as efficiency enhancement of the base plant as well as availability of low-cost fuel may also have significant impacts of costs of CCS as seen through illustrative international examples (Hu and Zhai 2017; Singh et al, 2017).

Finally, several 2nd and 3rd generation capture technologies (Table 6.5) are being developed with the aim of targeting not just lower cost but also other advantages such as reduced energy penalty, increased modularity and lower water consumption. Approaches here include membrane based capture, wherein increasing the selectivity is a major challenge and chemical looping, which also has the advantage of ready co-firing amenability with biomass (Zhu et al, 2018).

Table 6.7 Scale and technological readiness levels (TRL) of various CO_2 capture technologies as compared to SRCCS levels (Abanades et al, 2019).



Separation process	Application	TRL*		Comments
		2005	2015	
Absorption				
Physical	Industry	9	9	Commercial technology for the separation of H_2/CO_2 mixtures from syngas (<3 Mt CO_2/y).
	Pre-combustion	8	8	Most components are TRL 9, but hydrogen-based power generation is less mature.
Chemical	Industry	9	9	Commercial technology in refineries and for the natural gas sweetening.
	Post-combustion	7	8	Demonstrated at a capture rate of 1 Mt CO_2/y in the Boundary Dam CCS project.
Cryogenics				
Air separation	Industry	9	9	Commercial technology for oxygen production (<4000t O2/d).
	Oxy-combustion	5	7	Combustion island has been demonstrated up to 30 MW_{th}.
CO_2 anti-sublimation	Post-combustion	3	3	
High temperature solid looping				
Chemical looping	**Oxy-combustion**	**3**	**6**	Demonstrated at 1 MW_{th} pilot plant using hard coal and ilmenite as oxygen carrier
	Pre-combustion	2	3	
Calcium looping	**Post-combustion**	**2**	**6**	Demonstrated at a scale of > 1 MW_{th} using oxyfuel combustion-calcination
	Pre-combustion	2	2	Challenging sorbent regeneration at high pressure and temperature
Solid sorbents				
Adsorption	Industry	9	9	Commercial technology for natural gas sweetening and H_2 production (i.e. Port Arthur CCS project)
	Pre-combustion	8	8	Most components are TRL 9, but hydrogen based power generation is less mature.
	Post-combustion	**2**	**5**	CO_2 capture from flue gases by VPSA <2 t CO_2/d.
	Oxy-combustion	6	6	VPSA is commercial for oxygen production, but at low capacity (<500t O_2/d)
Low T G/S reactions	**Post-combustion**	**4**	**6**	Initial results from a 10 MW_e fluidized bed pilot
	Pre-combustion	3	5	Sorption enhanced water gas shift (SWEGS)
Membranes				
Polymeric membranes	Industrial	9	9	Commercial technology for natural gas sweetening (i.e. Sleipner CCS project)
	Post-combustion	**3**	**5**	Demonstrated at a capture rate of 1t CO_2/d using polymeric membranes.
Other membranes	Pre-combustion	3	3	
	Oxy-combustion	4	5	Oxygen production using Ion transport membranes (5 t O_2/d)

[Economic] The literature has broadly identified the costs of CCS to be the major hindrance to its deployment. The capital cost of a coal or gas plant with CCS is almost double than one without CCS (Morris et al, 2019). Additionally, based on the 13-44% increased fuel use for heat and compression requirements leads to a significantly heightened electricity cost with CCS (Table 6.). CCS costs are currently higher than the carbon prices with limited changes from the SRCCS period but they do also remain competitive with suitable changes in technological or policy configurations (Rubin et al. 2015a). Similar ranges of values have also been reported by other reviews on the subject (Budinis et al. 2018).

A major consideration that arises with the reported costs of CCS is consistency to these costs since a number of metrics have been reported – cost of CO_2 captured, avoided or abated (for detailed explanations, see (Rubin et al. 2013). Further, different underlying techno-economic assumptions may lead to vastly different costs even for the same technology levels.

Table 6.8 Costs and performance parameters of CCS in fossil fuel power plants (Rubin et al. 2015b)

Cost and Performance Parameters	NGCC with post-combustion capture	SCPC with post-combustion capture	SCPC with oxy-combustion capture	IGCC with pre-combustion capture
Reference plant without CCS: Levelized cost of electricity (USD/MWh)	42–83	61–79	56-68	82–99
Power plants with CCS				
Increased fuel requirement per net MWh (%)	13–18	21–44	24–29	20–35
CO_2 captured (kg/MWh)	360–390	830–1080	830–1040	840–940
CO_2 avoided (kg/MWh)	310–330	650–720	760–830	630–700
% CO_2 avoided	88–89	86–88	88–97	82–88

It must be noted that few previous years have also given rise to several demonstration scale projects of the order of 1-3 Mt-CO_2/year, which also contribute to the aforementioned estimates – at least to the capital costs. These projects have diverse CO_2 sources and sinks (Herzog 2017; Reiner 2016). This, in itself, gave some useful indications for future CCS cost estimates. For instance, there was external repowering for steam regeneration in the Petra Nova CCS project, which needs to be accounted for (Mantripragada et al. 2019).

Apart from the costs of CO_2 capture, recent work has also appeared on the costs of CO_2 transport and injection. As such, the costs of transport seem to reduce with increased economies-of-scale and the costs of injection depend on ideal depths, porosity, permeability and storage formation type (Middleton and Yaw 2018; Grant et al. 2018; Garg et al, 2017). In some cases, it has been noted that cost optimization of transport and storage infrastructure is necessary to ensure that overall system costs are minimum and significant amounts of CO_2 may be reliably sequestered.

It has been anticipated that reductions in CCS costs may lead to large-scale commercialization, which again can give rise to reduced prices through technological learning. Endogenous “learning-by-doing” is also accounted for within integrated assessments and has been shown to be a critical parameter in determining the efficacy of CCS in the energy systems. Learning approaches are likely to be more useful when dealing with gasification technologies and therefore investment decisions into CCS-ready power plants are crucial, especially as IGCC power plants are also expected to capture CO_2 with lower energy penalty (Rubin 2019).

[Environmental/Ecological, Sociocultural, and Institutional] Policy instruments for the viability of CCS are also frequently discussed in the literature. Suitable financial instruments include emission certification and trading, legally enforced emission restraints, and carbon pricing (Haszeldine 2016). Limiting emissions may necessitate early retirement if not changing the fuel source. The US 45Q tax credits have also attempted to link the CCS approaches to NETs by incentivizing direct air capture (Bellamy 2018).

The key challenges currently include acceptance of the technology by the public as well as policy makers, especially in developing country contexts, where the technology is viewed with some pessimism due to increases in cost of electricity as well as the tendency to reduce investments towards renewables. Moreover, technological challenges that have become better quantified include: ensuring reliable sequestration by proper regulation, failing which leakages may be substantial both during transportation and storage as quantified by (Alcalde et al. 2018); managing compensatory power due to loss in net capacity (indicated earlier); ensuring consistent cooling water supply.

Box 6.9 CCUS - What’s New Since AR5

[Placeholder-This is a placeholder for the SOD, we will include a short summary of important changes since AR5.]

6.4.2.6 *Bioenergy*

Bioenergy is energy from organic matter (biomass), i.e. all materials of biological origin that are not embedded in geological formations. Biomass can be used in its original form as fuel, or be refined to different kinds of solid, gaseous or liquid biofuels. Biomass fuels can be produced from agricultural, forestry and municipal wastes and residues, as well as from crops such as sugar, grain, and vegetable oil. Crops grown for use as biomass fuel can be grown on degraded, surplus and marginal agricultural land, and algae could, in the future, be exploited as a marine source of biomass fuel. These fuels can be used in all sectors of society, for production of electricity, for transport, for heating and cooling, and for industrial processes.

There are four main types of biomass: (1) energy crops, including food crops, (2) forest products (fuelwood, residues and processing, and post-consumer waste), (3) agricultural residues (harvesting residue, processing residue and food waste), and (4) animal manure.

[Geophysical] Although almost all studies on the bioenergy potential are based on FAO statistics, depending on the sources and the assumptions, there are significant differences on the potential estimates. There are uncertainties for all categories of biomass. However sharp variation exist regarding energy from agricultural land. According to IEA most pessimistic (no land available for energy farming, only utilization from residues) and optimistic scenarios (intensive agriculture concentrated on the better quality soils), the bioenergy potential in 2050 ranges from 40 to 1100 EJ (IEA 2007). Existing potential estimates range from 0 EJ/a up to more than 1,550 EJ/ The production of bioenergy is confronted by challenges of land availability, water scarcity, biodiversity concerns, and land degradation and these have often not been included within potential estimates (Offermann et al. 2011).

A comprehensive review has been carried out on the main studies on the potential estimates Biomass potential studies are broadly divided in two categories: what might be physically possible and might be socially, acceptable or environmentally responsible (Slade et al. 2011). Based on key assumptions, three main levels of potential have been estimated.

Table 6.9 Estimates of world bioenergy potential

Potential estimates	Key assumptions
Up to 100 EJ	• Very limited land available for energy crops. Contribution from wastes and residues in the range 17-30EJ
100 to 300 EJ	• food crop yields keep pace with population growth and • increased meat consumption. Little or no agricultural land is made available for energy crop production. New areas of marginal, degraded and deforested land ranging from twice to ten times the size of France (<0.5Gha). • Contribution from residues and wastes estimated at 60-120 EJ
300 to 600 EJ	• increases in food-crop yields will outpace demand for food, with the result that an area of high yielding agricultural land the size • of China (>1Gha) is available for energy crops. • Area of grassland and marginal land larger than India (>0.5Gha) is converted to energy crops

[Technological] Biomass for energy (bioenergy) encompasses both modern and traditional biomass [1] Bioenergy, both traditional and modern, remains the largest renewable energy supply today**.** It is estimated that bioenergy contributed in 2017 to 12.4% (46EJ) to the total final energy consumption (REN21 2019; IEA 2018e).

However, there are sharp differences in energy systems, value chains and contribution to different end uses for each category of biomass. Traditional biomass as a source of heat, particularly for cooking is predominant in the building sector whereas modern bioenergy is mainly used in industry for heating, transport and electricity

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[1] Traditional biomass for heat involves the burning of woody biomass or charcoal as well as dung and other agricultural residues

generation. Modern bioenergy accounted for more than two-thirds of global renewable heat consumption in 2018, with a higher penetration in industry (IEA 2019d).

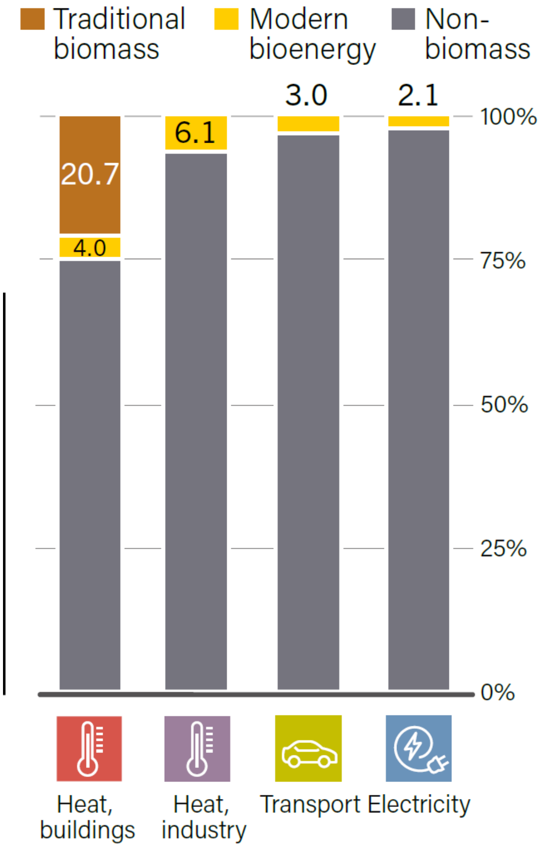


Figure 6.18 Estimated Shares of Bioenergy in Total Final Energy by End-Use Sector, 2017 Source (REN21 2019).

Traditional bioenergy is concentrated in developing countries particularly in Asia and sub Saharan Africa. It is the largest source of energy in sub Saharan Africa and accounts for two thirds of the final energy consumption with approximately 850 million people relying in this source of energy (IEA 2019e). The environmental and health impact resulting from cooking with traditional biomass is well documented. Household air pollution (HAP) is the single most important environmental risk factor worldwide. Based on estimates of solid fuels use, exposure to HAP cause 4.3 million premature death each year of which approximately 60% are women and children (WHO 2016). In sub Saharan Africa, it is estimated that cooking with polluting fuels and stoves was linked to almost half million premature deaths in 2018 (IEA 2019e). There are many studies on the pathways to limit the use of traditional biomass. These studies address the supply side with the deployment of improved technologies for the use of bioenergy such as improved stoves and the conversion of the primary energy (firewood) into charcoal with the deployment of improved kilns for charcoal made. They also address the demand side by switching to cleaner fossil fuels particularly LPG. According to the climate change and land report (Arneth et al. 2019) cleaner energy sources and technologies can contribute to adaptation and mitigating climate change and combating desertification and forest degradation through decreasing the use of traditional biomass for energy while increasing the diversity of energy supply (medium confidence).

Bioenergy systems have been described previously in detail by the IPCC Special Report on Renewable Energy. The tendency of bioenergy to sequester the carbon which is emitted by biological uptake makes it a zero-emission technology. Further, when this emitted carbon is also geologically sequestered, it is referred to as bioenergy with CO_2 capture and storage, which is the most prominent negative emission technology dealt within the IAM exercises.

[Economic] The costs of bioenergy systems, especially when integrated as BECCS are at high levels especially due to lack of technological readiness. As efficiency of such systems increase through the suggested approaches, the cost is likely to reduce 30-50% in the next three decades.

Co-firing of various technologies has shown to be increasing the energy penalty of CCS, as compared to fossil fuel with CCS power plants with conventional CO_2 capture technologies. However, chemical looping has been shown to be a promising generation technology where the range of LCOE and energy penalty may be equivalent or less for biopower (Bhave et al. 2017):

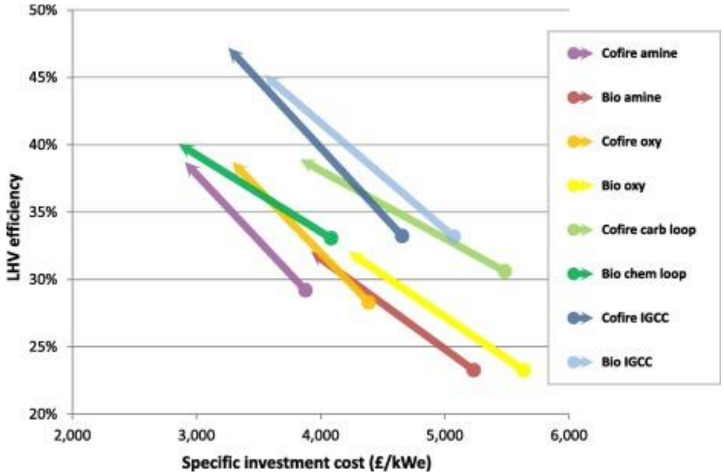


Figure 6.19 This estimate from (Bhave et al. 2017), i.e. cost versus efficiency trajectory could be adapted by giving broader ranges for all BECCS and CCS technologies. Incorporating several dots into value-clouds may be useful for the readers to make a broad judgements on the state-of-the-art technologies.

Similarly, biomass gasification also may have important role to play because of several higher-moisture waste biomass available that may be combined with other solid fuels to result in net-negative emissions (Al-Ansari et al. 2016; Pour et al. 2018; García-Velásquez and Cardona 2019; Roy et al. 2019). Most prominently, waste biomass has some potential gasification potential in incorporating net negative or net zero emissions, as required.

Efficiency enhancement through learning (as shown above) or by other approaches such as waste heat recovery also has strong carbon-negative impact on the overall energy system (Bui et al. 2017). There has been some discourse in this regard because other papers have concluded that higher efficiencies may in fact, result in less net-sequestered carbon because of less biomass requirements (Mac Dowell and Fajardy 2017). Combined heat and power (CHP) approaches have also been frequently talked about such that the heat may be used for drying/dewatering purposes (Uris et al. 2015; Groth and Scholtens 2016), however, there are limits due to the capital costs and limited distance of heat transfer that may be done sustainably.

Algae-to-energy systems may reduce freshwater and land requirements by large-scale bioenergy cultivation off the coasts, especially in countries with longer coastlines. These systems may sometimes require different chemical conversion approaches due to very high moisture contents (such as hydrothermal or digestion) (Sun et al. 2019; Beal et al. 2018), where again EROI may be compromised due to low usable energy yield.

[Environmental/Ecological] Bioenergy systems' potential is largely limited in various regions due to large water and energy requirements. Land use and water-use estimates for BECCS are orders of magnitude higher than conventional energy generating technologies. The estimates have been presented by several researchers (Bonsch et al. 2016; Kato and Yamagata 2014; Séférian et al. 2018). We will need to harmonize the resource use estimates for fertilizers, land and water as presented by several papers to units of kg/kWh (since our section deals with electricity generation) after assigning baseline efficiency parameters. Some sort of variation to the illustration presented by (Smith 2016) can be used as shown below:

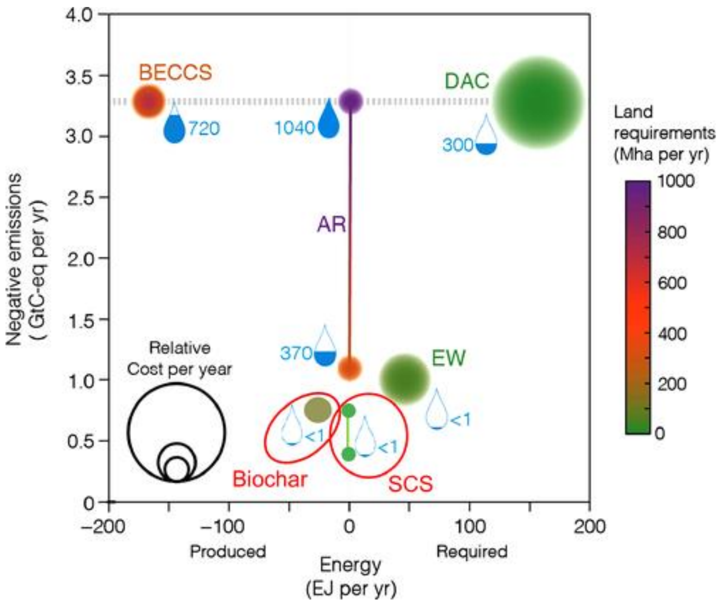


Figure 6.20 Illustration from (Smith 2016) which could be adapted for the various estimates on bioenergy and BECCS-only after harmonizing the results to electricity units, instead of carbon units.

Life-cycle results of BECCS systems have shown the need for deep decarbonization of the energy sector for negative emission systems, such as BECCS to be successful in delivering high-energy low-emissions output. This is because bioenergy systems are logistically challenging (especially when combined with CO_2 sequestration) and run the risk of reducing energy return on investment (EROI) or having net-zero or positive emissions if not sustainably managed (for example, through the reuse of fertilizing nutrients). These life-cycle results have been talked about in significant detail by (Creutzig et al. 2019a) and (Fajardy and Mac Dowell 2017) and (Mac Dowell and Fajardy 2017). BECCS systems require suitable climatic conditions for growth of bioenergy crops as well as presence of suitable geologic storage for reliable, long-term CO_2 sequestration. This was an important target research area for the *ERL* series of review papers on negative emission technologies as well (Minx et al. 2018) Fuel availability may also become costly due to competition of agricultural land availability (Muratori et al. 2016).

[Institutional] Societal support for BECCS systems may be difficult and is difficult to capture in IAM (Van Vuuren et al. 2017b; Gough et al. 2018; Scott and Geden 2018). Flexibility between energy systems and bioenergy systems has been suggested as an important earmark towards more robust BECCS deployment (Sanchez and Kammen 2016; Bauer et al. 2018). Most IAM results have given prominent place to BECCS because of shrinking carbon budgets and significant availability of bioenergy resources but also recent carbon tax availability for carbon sequestration (Fawcett et al. 2018). Several studies within the US have discussed BECCS potential in a further regional context made possible by significant data availability in various domains (Sanchez et al. 2015; Dale et al. 2017; Gassman et al. 2017; Costanza et al. 2017). Some of the appropriate considerations have been identified for the near-term BECCS deployment such as high natural gas prices and proximity for reliable CO_2 sequestration sites (Baik et al. 2018; Muratori et al. 2017). Important coverage has also been provided to sustainability aspects due to projected long-term changes in hydrology due to bioenergy crop production which can be connected to 6.6.8 (Hejazi et al. 2015; Song et al. 2016).

The role of BECCS and bioenergy in China have been explicitly discussed. In the short-term, Chinese requirements for BECCS are not as large as the developed economies with significant solar, wind and nuclear deployment, as shown by different papers (Pan et al. 2018; He et al. 2016; Jiang et al. 2018). Analysis also reveals the need for specific incentivizing of bioenergy for it to play a prominent role in the energy mix (Clare et al. 2016; Liu et al. 2017). In a developing economy context, it is very important to harmonize food security with energy security and thus, some focus has been given to bioenergy production in the large marginal lands present throughout the country (Xue et al. 2016; Shu et al. 2017; Jiang et al. 2015). Some recent attention has also been given to co-firing especially because of the *high-efficiency, low-emission* (HELE) power plants in China, which can be used to deliver net negative emission in tandem with biomass gasification especially to assimilate health and climate targets simultaneously (Lu et al. 2019).

Box 6.10 Bioenergy - What's New Since AR5

[Placeholder-This is a placeholder, for the SOD, we will include a short summary of important changes since AR5.]

6.4.2.7 *Fossil Energy*

Fossil fuels play a unique role in climate mitigation. On the one hand, the primary mechanism for reducing emissions is to eliminate the use of freely-emitting fossil fuels. On the other hand, fossil energy combined with CCUS provides a means to produce low- or zero-carbon energy while utilizing the immense base of fossil energy worldwide and limiting the economic disruption to countries and regions with substantial unused fossil energy.

[Geophysical] Inventories for fossil fuel resources and reserves have been prepared for a significant number of years and the resource base is continually augmented annually based on further exploration. The first major issue is the reporting definitions themselves. Resources and reserves are reported differentially reported by the governments of various countries. As a result of differences in reporting practices as well as exploratory exercises, uncertainties remain regarding the fossil energy resource base. These include (Speirs et al. 2015): uncertainty in reservoir size, new exploration levels; efficacy of enhanced recovery techniques (say through injecting CO_2); operating costs over a lifetime, price of substituting and negative consequences to air, water, health and other ecosystem services.

Because these are natural formations, fossil resources are distributed unevenly throughout the globe (Figure 6.). Coal represents the largest remaining resource. Oil and gas resources are an order of magnitude smaller. Significant impacts of unconventional fossil fuels have been seen in the last decade through technological development globally (Table 6.). Discovered ultimate recoverable resources of both unconventional oil and gas are comparable to conventional oil and gas (Court and Fizaine, 2017). These are used to define the resources which cannot be recovered using standard primary or secondary recovery techniques and are characterized by different reservoir parameters and production profiles (low permeability, high depth, initiated by large water production earlier on, and so on).

Evolution of the unconventional gas sector has abetted changes in energy systems, especially in North America. Price analysis shows differential impacts on the pricing in US gas pricing mechanisms with seasonal fluctuation in pricing in the Henry Hub becoming insignificant now with other projections showing limited impact of the shale gas revolution to the carbon mitigation trends in the long-term (Geng et al. 2016; Few et al. 2017; Cooper et al. 2018). Similarly, there is some disagreement as to the international impacts of the US shale gas boom (Bernstein et al. 2016); Aruga, 2016).

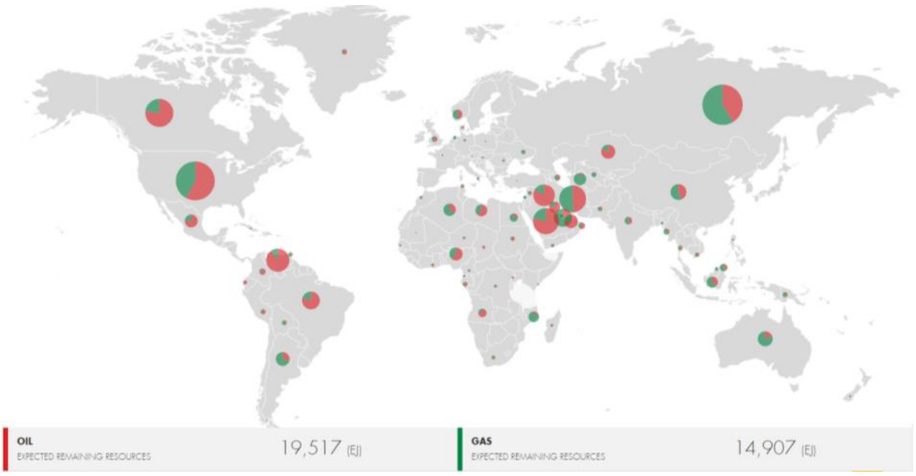


Figure 6.21 Geographical distribution of oil and gas resources. The current map is taken from Shell Global Energy Resources Database, but this may be suitably modified. Coal is currently not included in this figure since the figure gets largely skewed because of much larger coal resources.

Apart from global estimates as presented above, attention must be given to regional exploratory practices since they may affect the resource base in two ways. First, newer basins may continue to be explored since unconventional oil and gas exploration is still in a nascent stage in various countries. On the other hand, regionalized assessments may eliminate several reservoirs due to difficulties in extraction as presented by engineering and operational factors. Therefore, illustrative assessments in national/regional context must also be looked at critically (Saussay 2018) Liang et al, 2017). These updated resource inventories have also been taken up gradually by global modelling exercises (Huang et al. 2017; Feijoo et al. 2018).

Table 6.4 Unconventional oil resources (Hongjun et al, 2017). Other data have also been presented by Caineng et al (2017).

Region	Resources/10^8 t									
	Heavy oil		Oil sand		Tight oil		Oil shale		Unconventional oil	
	Recoverable	Geological	Recoverable	Geological	Recoverable	Geological	Recoverable	Geological	Recoverable	Geological
North America	318	3 177	395	3947	91	2 540	699	3 279	1 503	12 943
Russia	88	449	156	599	77	1 555	570	1 927	891	4 530
South America	409	4 092	0	0	68	1 954	150	280	627	6 326
Europe	82	224	18	54	26	700	354	2 334	480	3 312
Asia	130	502	48	273	79	2 050	120	137	377	2 962
Middle East	177	1 208	0	0	13	357	102	176	292	1 741
Africa	63	186	24	140	42	1 191	68	115	197	1 632
Oceania	0	0	0	0	18	871	36	97	54	968
Total	1 267	9 838	641	5013	414	11 218	2 099	8 345	4 421	34 414

[Economic] There is significant variation in the costs of extraction for oil, gas and coal based on ease of extraction as well as geography. Selling prices of such fuels are also affected by subsidies as well as global demand for such fuels. The costs of fossil fuels also depend on what these costs encompass. First, regarding the actual costs of production themselves, Figure 6. shows that the variance in terms of resources. Thus, for coal, the prices of shallow lignite deposits that are currently being extracted are very low followed closely by currently mined out hard coal reserves. Similarly, the costs of extraction of conventional gas reserves is significantly less than large amounts of shale gas resources. 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 cleaner fuels such as biomass, where intensive processing reduces EROI (Hall et al, 2014).

The cost of production itself is different from the price at which the fuel is sold or utilized which depends on demand-supply dynamics as well as end-sector usability of the fuel. For instance, gas wellhead price in the US has declined by almost 2/3rd due to vast abundance of gas. Similarly, the global price of crude has declined from almost $ 100/bbl to $ 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. Selling prices have fluctuated widely for decades.

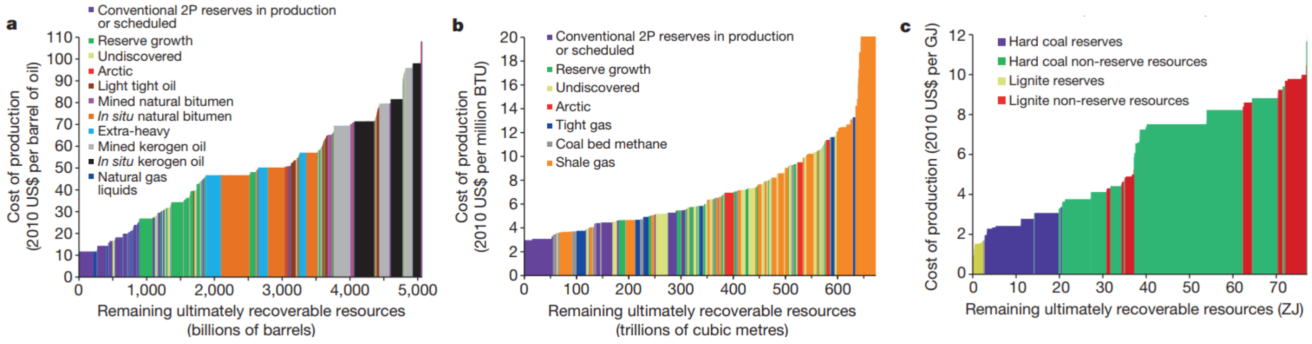


Figure 6.22 Costs of production for (a) oil, (b) gas and (c) coal as a function of recoverable resource (McGlade and Ekins 2015)

[Environmental/Ecological] Internalizing the health and climate externalities of the fuel extraction as part of the stated costs has also been attempted. In this context, there are some differences in the way the literature may be perceived. Tanaka et al (2019) projected that coal to gas switching is consistent with climate mitigation targets in a wide range of scenarios and techno-economic parameters. However, the leakage in shale gas systems of fugitive methane emission is still a widely debated aspect with estimates suggesting leakage between 1.5% (less than conventional gas systems) to 10% (three times as much as conventional gas systems). As a result, making quantitative judgements regarding the externality costs of unconventional gases is difficult (Peischl et al. 2015; Lyon et al. 2015; Baillie et al. 2019) and alternative recent work seeks to reconcile these divergent estimates of leakage (Zavala-Araiza et al. 2015; Alvarez et al. 2018). Moreover, produced water from such formations is moderately to highly brackish, and treating such waters has large energy and cost implications (Singh and Colosi 2019; Bartholomew and Mauter 2016).

[Sociocultural, Institutional] Significant attention has been paid to fossil fuel subsidies reduction, which have been valued of the order of $ 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) Coady et al, 2015). Subsequent reforms have also been suggested by different researchers who have estimated reductions in CO_2 emissions may take place if these are removed (Mundaca 2017). Others have also proposed that such reforms would create the necessary framework for enhanced investments in social welfare – through sanitation, water, clean energy – with differentiating impacts (Edenhofer 2015; Dennis, 2017). There is however some disagreement in these perspectives as other studies have found out negligible or negative social benefits in removal of such subsidies (Jewell et al. 2018; Wesseh and Lin 2017).

6.4.2.8 *Geothermal Energy*

[Geophysical] 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,. Various studies suggest the geophysical potential of geothermal resources is 10 to 100 times the current generation. 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. Global geothermal technical potential is comparable to global primary energy supply in 2008. For electricity generation, the technical potential of geothermal energy is estimated to be between 118 EJ/yr (to 3 km depth) and 1,109 EJ/yr (to 10 km depth). For direct thermal uses, the technical potential is estimated to range from 10 to 312 EJ/yr (IPCC 2011).

There is an enormous potential for direct geothermal heat from aquifers: only 0.15% of the annual global final energy consumption is supplied by geothermal direct heat. The main causes for the large mismatch between potential and developed geothermal resources are high up-front costs for geothermal projects, decentralized production of geo-thermal heat, lack of uniformity among geothermal projects, geological uncertainties, and geotechnical risks (Limberger et al 2018).

[Technological] 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.

[Economics] The following figure summarizes the key economic indicators for geothermal power plants. However, given the limited number of plants commissioned, these indicators depend heavily on the site characteristics

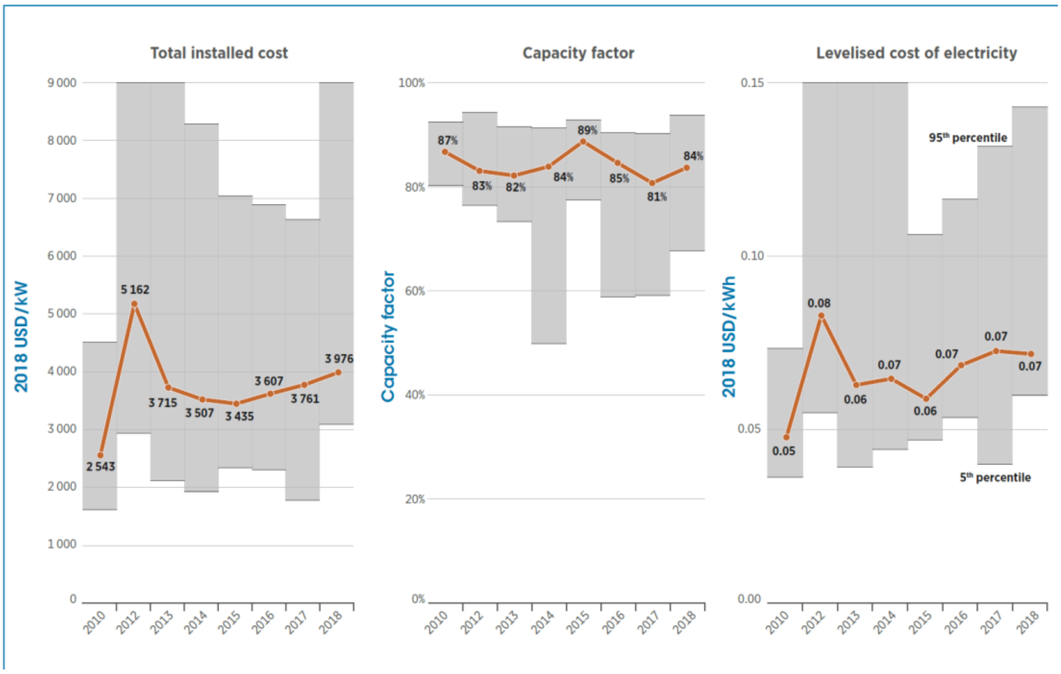


Figure 6.23 Global weighted average total installed costs, capacity factors and LCOE for geothermal power, 2010 Source (IRENA, 2018)

[Environmental/Ecological and Sociocultural] In the last 40–50 years, geothermal development have revealed that it is not totally free from adverse environmental impacts (Mahmood ARSHAD et al, 2019). The impacts may occur as air pollution, noise pollution, water pollution, land and water use, land subsidence, thermal pollution, aesthetics, and other catastrophic events such as seismic events. About thermal pollution, geothermal power plants reject a lot more heat than other type plants per unit of electricity generated. However, in comparison with alternatives, geothermal plants are among the most environmentally benign (DiPippo, 1991). Environmental impact occurs levels of the process and its impact is different according to the temperature.

Table 6.11 Issues associated with geothermal power. (Source; Trevor M. Hunt , 2001, Institute of Geological and Nuclear Sciences, Taupo, New Zealnad)

	Low-temperature systems	High-temperature systems	
		Vapour-dominated	Liquid-dominated
Drilling operations:			
Destruction of forests and erosion	●	● ●	● ●
Noise	● ●	● ●	● ●
Bright Lights	●	●	●
Contamination of ground-water by drilling fluid	●	● ●	● ●
Mass withdrawal:			
Degradation of thermal features	●	● ●	● ● ●
Ground subsidence	●	● ●	● ● ●
Depletion of groundwater	○	●	● ●
Hydrothermal eruptions	○	●	● ●
Ground temperature changes	○	●	● ●
Waste liquid disposal:			
Effects on living organisms			
surface disposal	●	●	● ● ●
reinjection	○	○	○
Effects on waterways			
surface disposal	●	●	● ●
reinjection	○	○	○
Contamination of groundwater	●	●	●
Induced seismicity	○	● ●	● ●
Waste gas disposal:			
Effects on living organisms	○	●	● ●
Microclimatic effects	○	●	●

○ No effect ● ● Moderate effect
● Little effect ● ● ● High effect

Box 6.11 Geothermal Energy - What's New Since AR5

[Placeholder-This is a placeholder. For the SOD, we will include a short summary of important changes since AR5.]

6.4.2.9 *Marine Energy*

The oceans of the world are a huge source of untapped energy. The ocean contains energy in various forms a few of which include temperature- and salinity gradients, tides, tidal streams, ocean currents and waves.

The elevation differences between high and low tides can be used for electricity generation. Tidal energy appears in two forms: tidal potential energy and tidal current energy. Global total tidal energy geophysical potential is estimated at between 500 and 1000 TW h/yr (Melikoglu 2018); Global, technically harvestable tidal power from areas close to the coast, is estimated at nearly 1 TW.

Ocean wave energy is one of the most abundant clean, frequent, renewable, periodic and predicted energy sources around the globe. It has been reported that ocean waves can provide up to 2 TW of electricity. The global offshore wave power is estimated at 32,000 TW h/yr, which is reduced to 16,000 TW h/yr when considering the direction of the energy (Reguero et al. 2015).

Ocean thermal energy conversion (OTEC). The temperature gradients in the ocean can be exploited to produce energy. Finally, according to the IRENA global OTEC potential is nearly 300 EJ (or nearly 83,300 TWh) per annum. Salinity gradient energy is also known as osmotic power, according to the IRENA global technical and theoretical salinity gradient potentials could be nearly 5200 and 27, 700 TWh per annum (IRENA, 2014d).

6.4.2.10 *Waste-to-Energy*

Waste to energy (WtE) is a term that describes technologies that convert non-recyclable waste into energy such as heat, fuel, and electricity. Rapid growth in global population has resulted in increase in municipal solid waste generation and high demand for sustainable energy sources (Khalil et al. 2019). Waste-to-energy technologies have been hugely relied on globally as an alternative for sustainable energy generation and municipal solid waste management (Maghanaki et al. 2013).

In 2015, the global market size of WtE stood at $25 billion, and it is predicted to increase in coming years. The rise in the global WtE market revenue result from high demand with biological technology taking the lead. Countries in the OECD region are expected to benefit more while China and India in Asia will benefit less.

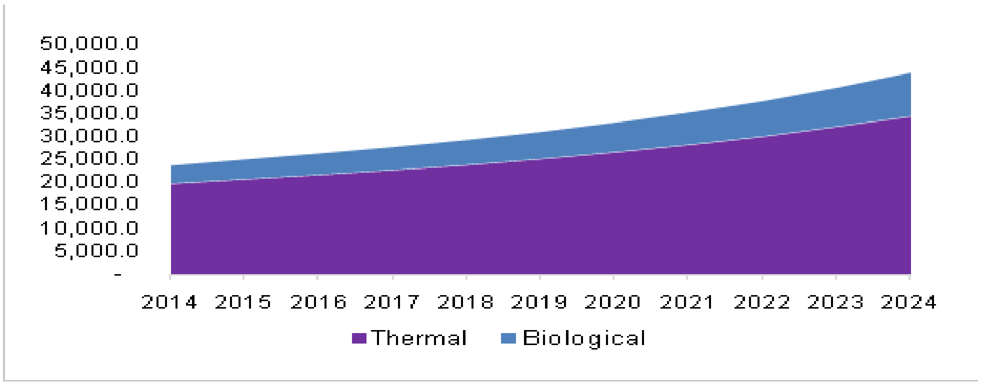


Figure 6.24 Global WtE Market revenue by technology, 2014-2024 (Grand View Research 2016)

WtE technologies contribute to reduction of volume of waste whiles producing sustainable energy to meet the current demand. Incineration for example, can reduce the volume of waste by 80-95%. However, Urso Camposet al (2008) caution that if the proper safety measures are not taken when adopting WtE technologies for waste treatment, they can generate more carbon dioxide emission, than coal, natural gas or oil.

6.4.3 Energy Storage for Low-Carbon Grids

In response to the climate change challenge, the global energy system is expected to integrate increasing amounts of intermittent renewable generation. Analysis has shown that energy storage can deliver multiple economic and security benefits to such low carbon systems. Specifically, grid scale storage technologies have the potential to reduce: investment in low carbon generation by enhancing the ability of the system to absorb renewables; investment costs in back-up generation by contributing to the security of supply; the need for interconnection and transmission investment; the need for distribution network reinforcement to support the electrification of transport and heat.

It is also clear that different types of energy storage will be needed to address these requirements. These range from electrical energy storage technologies that deliver mostly energy, such as pumped hydro, compressed air, flow batteries, hydrogen and liquid air, to those that deliver mostly power such as flywheels and supercapacitors, to those that deliver some combination of power and energy such as batteries, along with technologies for thermal energy storage. In this context, a summary of the leading energy storage technologies is presented, including a comment on where the technology is heading. Their grid applicability is summarised in Table 6.512 and key features compared in Table 6.613. It should be noted that, with the exception of lithium ion batteries and pumped hydro, there are few mature global supply chains for the energy storage technologies presented here. This means that costs today can be relatively high, but also that there are significant opportunities for cost reduction in the future, both through technology innovation and through manufacturing scale. Current costs are included where available.

6.4.3.1 *Pumped hydro energy storage (PHES)*

Technology operation: PHES uses excess electricity to pump water into an elevated reservoir and releases it at a later time when electricity is needed, where the force of the falling water drives turbines to generate electricity. PHES is a well-established technology, of high technical maturity (Rehman et al. 2015), however the construction itself can cause disruption to the local community and environment, the initial investment is costly and there tend to be extended construction periods delaying the return on investment. Pumped hydro is best suited for longer periods of energy storage, from multiple hours to days and beyond.

Advances and research needs: Conventional PHES plants can provide power regulation only during generation, not during pumping. Advanced pump-turbines are being developed which allow both reversible and variable-speed operation, enabling finer frequency control and improving the round-trip efficiency (Ardizzon et al. 2014). New possibilities are being explored for small-scale PHES installations and underground siting, potentially in abandoned mines and caverns, which could be developed reasonably quickly.

6.4.3.2 *Compressed Air Energy Storage (CAES)*

Technology operation: Excess 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. When the compressed air is allowed to expand, it drives gas turbines to generate electricity. While conventional CAES has used natural gas to power compression, new CAES technologies, termed “No fuel CAES”, have found low carbon ways to control thermal losses during compression and expansion (Wang et al. 2017c). This is a mature technology in use since the 1970s, however it is still considered to be in the commercial stage, due to the low number of installations to date (Wang et al. 2017b). This is largely due to the high initial investment. CAES is best suited to energy storage periods in the multiple hour range.

Advances and research needs: Efficiencies can be improved by two methods for controlling heat losses: adiabatic CAES (A-CAES) uses thermal storage to capture the heat generated during compression for later use during expansion (Wang et al. 2017c, 2016); isothermal CAES (I-CAES) minimises heat loss through gradual stages of compression and heat-exchange (Wang et al. 2017c; Steinmann 2017). 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). 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).

6.4.3.3 *Liquid Air Energy Storage (LAES)*

Technology operation: LAES is also called cryogenic energy storage, as it uses electricity to cool air to -196 °C and stores it in the condensed liquid form (largely nitrogen) in large, insulated tanks. To release electricity, the ‘liquid air’ is expanded through heating, driving gas turbines. Low grade waste heat can be utilised, providing opportunities for integrating with industrial processes to increase whole system efficiency. There are clear synergies with the existing liquid gas infrastructure, which can be exploited (Peters 2016). This technology is in the early commercial stage, with the UK at the forefront of development in this area (Regen 2017; Brandon et al. 2015). LAES is best suited to energy storage periods in the multiple hours range.

Advances and research needs: 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).

6.4.3.4 *Thermal Energy Storage (TES)*

Technology operation: 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). TES can uniquely be integrated into energy systems, buildings or industrial processes to capture and reuse waste heat (particularly important as demand for cooling is expected to grow (Peters 2016; Elzinga et al. 2014). Sensible TES is well developed and widely used; latent TES is less developed with few applications and thermochemical TES is the least developed, with no application as yet (Brandon et al. 2015). LAES, discussed above, is actually a hybrid form of latent TES and CAES. Pumped Thermal Energy Storage (PTES), a hybrid of sensible TES and CAES, 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). This technology is only in the demonstration stage of development (Smallbone et al. 2017). TES is best suited to energy storage periods in the multiple hours to days range, depending on the technology.

Advances and research needs: The potential for extended (months to years), high density energy storage in thermochemical TES (Brandon et al. 2015) is extremely high, with energy densities comparable to that of batteries (Taylor et al. 2012), but the material costs are currently prohibitive. Research into novel materials and lower cost manufacturing processes is therefore needed, but also into the relationships between properties and function across all length scales: from materials up to devices and whole systems (Brandon et al. 2015).

6.4.3.5 ***Flywheel Energy Storage (FES)***

Technology operation: 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. Flywheels are a relatively mature storage technology, but not widely used, despite their many advantages over electrochemical storage (Dragoni 2017). 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 than batteries and supercapacitors, they are a valuable competitor where long calendar and cycle lives are required. Flywheels are best suited to applications when power is needed, rather than energy, in the sub-second to seconds range.

Advances and research needs: 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). High-temperature superconductor bearings may extend the time energy can be stored economically, by further reducing friction losses (Amiryar and Pullen 2017). Higher rotational speeds may be achievable through the adoption of ultrahigh speed machines, such as induction and permanent magnet synchronous machines (Yulong et al. 2017).

6.4.3.6 ***Batteries***

Technology operation: A rechargeable battery cell has two electrodes, a cathode and an anode, surrounded by an electrolyte, allowing the movement of charge carriers or ions. The cell is charged by using electricity to drive ions from one electrode to another. This process is reversed on discharge and a usable electric current is produced (Crabtree et al. 2015). There are many types of batteries, all having unique features and suitability. Lead-acid batteries (LABs) have been widely used for automotive and grid applications for decades and can be considered to be well established (May et al. 2018). High temperature batteries (HTBs) include sodium sulphur (Na-S) and sodium nickel chloride ($NaNiCl_2$) or ZEBRA batteries, which are commercially available and proven in grid applications (Kumar et al. 2017; Delmas 2018). Lithium ion batteries (LIBs) are emerging, with many recent grid scale projects in development (Crabtree et al. 2015). LIBs are attractive for electric vehicles (EVs) and 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, due to a range of (chemistry dependent) degradation mechanisms, and the use of hazardous or costly materials in some variants. While LIB production costs are decreasing (Schmidt et al. 2017b; Nykvist et al. 2015), the risk of thermal runaway, which could ignite a fire (Gur 2018), and concerns about long-term resource availability and global cradle-to-grave impacts (Hammond and Hazeldine 2015) need to be addressed. Batteries offer flexible energy storage with the ability to deliver both power and energy and are particularly suited to applications in the 0.5 to 4 hour range.

Advances and research needs: Cost reductions through economies of scale are a key area for development. Extending the usable life of the battery can bring down the overall costs of the technology and mitigate the environmental impacts (Hammond and Hazeldine 2015), therefore understanding battery degradation is important. The liquid, air-reactive electrolytes of conventional LIBs are the main source of their safety issues (Gur 2018; Janek and Zeier 2016), so solid state batteries, where 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).

6.4.3.7 ***Supercapacitors (Scap)***

Technology operation: 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. 2017b; Brandon et al. 2015) and can operate from -40 to 65°C. Their commercial status is limited by costly materials and additional power electronics required to stabilise their output (Brandon et al. 2015). Supercapacitors are best suited to applications when power is needed, rather than energy, in the sub-second to seconds range.

Advances and research needs: Progress in this area includes the development of high energy supercapacitors and a hybrid device combining the features of a Li-ion battery and a supercapacitor (Gonzalez et al. 2016). Both of these options have the potential to improve the economic case for supercapacitors, either by reducing manufacturing costs or extending their service portfolio. In addition, cheaper materials are sought (Wang et al. 2017a).

6.4.3.8 ***Hydrogen and Reversible Hydrogen Fuel Cells (H/RHFC)***

Technology operation: Hydrogen is a carbon-free fuel holding three times the amount of energy held by an equivalent mass of petrol, but occupying a large volume. Reversible hydrogen fuel cells (RHFCs) use excess electricity to split water into hydrogen and oxygen through the process of electrolysis, recombining these to generate electricity. For grid scale storage, salt caverns can be used to store large quantities of hydrogen at moderate pressures, that could provide inter-seasonal storage. Hydrogen is a flexible fuel with diverse uses, such as heating and transport and has been widely used in industry for decades. RHFCs are still in the pre-commercial stage, due to prohibitive production costs. Hydrogen offers the potential for long term energy storage, in the range of hours, to days or even weeks.

Advances and research needs: Research in this area 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).

6.4.3.9 ***Redox Flow Batteries (RFB)***

Technology operation: Redox flow batteries use two electrolyte solutions, usually liquids, but solid or gaseous forms may also be involved, stored in separate tanks and pumped over/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. RFBs are reversible, operating in “electrolyser” mode during charge, regenerating the reduced and oxidised forms in the electrolytes which are used up during discharge or “fuel cell” mode (Arenas et al. 2019). There are two commercially available types today: vanadium and zinc bromide and both operate at near ambient temperatures, incurring minimal operational costs. RFBs are best suited to energy storage periods in the multiple hours range.

Advances and research needs: Lower cost and safer chemistries are emerging which also offer the prospect of improving energy density (Brandon et al. 2015), as larger quantities of electrolyte become cost-effective. Another approach is to use air for the cathode redox reactions, resulting in a lower cost liquid-air flow battery, for example zinc-air flow batteries. A new membrane-free design eliminates the need for a separator and also halves the system requirements, as the redox couples can coexist in a single electrolyte solution (Navalpotro et al. 2017; Arenas et al. 2018).

Table 6.52 Suitability of the energy storage technologies to provide grid services

Service	**PHES** [42,43]	**CAES** [12,42,8]	**LAES** [8,44]	**TES** [14,45,46]	**FES** [20,42]	**Batteries** [42,29,25,26,27,22,47]	**Scap** [12,28]	**RHFC** [28,48]	**RFB** [42]
Energy Arbitrage	✓	✓	✓			✓		✓	✓
Capacity firming	✓	✓	✓	✓	✓	✓		✓	✓
Seasonal storage	✓			✓				✓	
Enhanced frequency response					✓	✓	✓	✓	✓
Fast frequency response	✓	✓	✓		✓	✓	✓	✓	✓
Voltage support	✓	✓	✓		✓	✓	✓	✓	✓
Black start	✓	✓	✓			✓		✓	✓
Short term reserve	✓	✓	✓			✓		✓	✓
Fast reserve	✓	✓			✓	✓			✓
Islanding		✓	✓	✓		✓		✓	✓
Upgrade deferral	✓	✓	✓	✓	✓	✓	✓	✓	✓
Uninterruptible power supply					✓	✓	✓	✓	✓

Table 6.63 Qualitative comparisons of the technologies presented .

Feature	**PHES** [1,42,15,43]	**CAES** [42,4,37,49,50]	**LAES** [4,11,12,3,49,10,51]	**TES** [12,15,51]	**FES** [18,17,20,42]	**LIB** [12,28,52,53,42,29]	**HTB** [42,28]	**LAB** [12,22,42]	**Scap** [12,28,54]	**RHFC** [28,12,48]	**RFB** [42,12]
Energy capacity	Very high	High	High	High	Low	Very High	High	High	Low	Very High	High
Energy density	Low	High	High	High	Low	Very high	High	Low	Low	Very high	Low
Power rating	Very high	High	High	Low	High	High	Low	Medium	High	Low	High
Power density	Very low	Low	Low	Low	Very high	Very high	Medium	Medium	Highest	Medium	Low
Response time	Good	Slow	Good	Slow	Very fast	Very fast	Very fast	Very fast	Very fast	Very fast	Very fast
Efficiency	Good	Good	Good	Low	High	High	Medium	High	Very high	Low	Good
Storage duration	Long	Long	Long	Long	Very short	Medium	Medium	Short	Very short	Long	Long
Lifespan	Very Long	Very long	Long	Long	Long	Adequate	Long	Short	Long	Short	Long
Self-discharge	Low	Low	Low	Low	Very high	Low	Low	High	Very high	Low	Low
Degradation	Low	Low	Low	Low	Low	High	High	High	Low	High	Low
Energy cost ($/kWh)*	5-100	2-84	260-530	3-60	1,500-6,000	473-1,260	263-735	100-500	380-5,200	3,230-5,800	315-1,680
2030 cost ($/kWh)*	5-100	2-71			979-3917	77-574	116-324	53-237		1,420-1,620	108-576
Power cost ($/kW)*	500-1,500	500-1,500	900-2,000	100-600	130-500	900-3,500	300-2,500	105-473	130-515	1,800-2,000	1,000-4,000
Materials	Abundant, cheap, safe	Abundant, cheap, safe	Abundant, cheap, safe	Abundant, cheap, safe	Costly	Limited, costly, toxic	Abundant, cheap, hazardous	Abundant, cheap, toxic	Limited, costly, toxic	Costly catalysts, membranes	Limited, costly, toxic
Environmental impact	High	Low	Low	Low	Low	Uncertain	Low	Low	High	Very low (if clean H2)	Low
Safety/risk	Reservoir collapse	Very safe	Cryogenics	Very safe	High speed rotor	Thermal runaway	Sulphur	Toxic lead	Safe to operate	Explosive	Toxic materials
Site availability	Low	Good	High	High	High	High	High	High	High	High	High
Maturity	Mature	Commercial	Early commercial	Commercial	Commercial	Demonstration	Commercial	Mature	Demonstration	Demonstration	Commercial

* - The suitability of a technology to either power or energy applications is reflected in the difference between power and energy cost, however power costs may not be reliable, as they are often determined from the energy costs. Costs given here are energy/power installed costs and are not necessarily comparable.

6.4.4 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. Recent developments, improvements and on-going R&D in hydrogen/ammonia production and consumptions and advanced electricity transmission infrastructure may prove important to support energy system decarbonisation.

6.4.4.1 *Hydrogen: Low-Carbon Energy Fuel*

Hydrogen (H_2) is considered as one of the key low-carbon energy fuels in future low carbon energy system (Rehman et al. 2015). Hydrogen is carbon-free and has a high conversion efficiency (Ardizzon et al. 2014) to electricity. One significant potential for hydrogen to contribute to decarbonisation is providing low-carbon heat to buildings and industrial processes. Furthermore, hydrogen fuel-cell based vehicles could supply heavy-duty vehicles (e.g. buses, trains and lorries) and potentially lighter vehicles for longer-range journeys, where the need to store and carry large amount of energy is greater than short journeys (Wang et al. 2017c,b, 2016; Steinmann 2017). There is also an opportunity for hydrogen to replace natural gas based electricity generation, potentially enabling significant reduction in emissions in electricity system.

Hydrogen can be produced from different processes including: (a) steam methane reforming (SMR) (Pimm et al. 2014), (b) autothermal reforming (ATR) (Luo et al. 2014), (c) biomass gasification with carbon capture and storage (CCS) (Venkataramani et al. 2016), and (d) from renewables in an electrolysis process (Peters 2016). In Table 6.7, the characteristics of different hydrogen production processes are presented (Regen 2017; Brandon et al. 2015; Taylor et al. 2012).

Table 6.74 Key performance and cost characteristics of different hydrogen production technologies

Technology	Efficiency (%)	CO_2 Capture Rate (%)	Cost Estimates (£/MWh H_2)
SMR + CCS	65-74	90	32-57
ATR + CCS	89	96	28-46
Biomass Gasification + CCS	46-60	Potential to achieve negative emissions	93-106
Electrolysis	92	-	90

One advantage of SMR/ATR based processes relates to the use of existing gas infrastructure for transport of natural gas, hence the natural gas can be delivered to appropriate locations. Therefore, SMR/ATR processes can be performed close to the hydrogen demand centres. Consequently, any challenges associated with transport of hydrogen would be bypassed. However, a major challenge in employing SMR/ATR in the long-run is the residual carbon emissions. Advanced electrolysis processes and technologies can be applied to produce hydrogen by renewable generation, for example power-to-gas (P2G) (Elzinga et al. 2014). Recent developments and improvements in hydrogen production technologies support the growing potential importance of hydrogen as the future energy fuel. This includes the increase in efficiency and reduction in cost of the gas-conversion technologies (e.g., SMR, ATR) (Taylor et al. 2012) as well as development of advanced hydrogen production technologies (e.g., mainly electrolysers; solid oxide electrolysis cell (SOEC)) (Peters 2016).

Utilising renewables (e.g., wind in north of Europe and solar in Africa) to produce hydrogen could be linked to the development of a hydrogen economy (see box in Seciton 6.6). If renewable electricity production were to be used for remote production of hydrogen, this would reduce the overall costs of grid connection and challenges associated with integration of intermittent renewable generation.

However, production of hydrogen in remote areas would require hydrogen transportation over long distances (e.g., hydrogen would be produced in middle east from solar, and it would be shipped to Europe in a form of energy carrier), including local distribution and intermediate storage capabilities needed to deliver hydrogen to the demand centers (e.g., refueling station or power plants) (Smallbone et al. 2017).

Within a country or region, 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 (Smallbone et al. 2017; Kolpak and Grossman 2011). For large-scale transportation, hydrogen must be pressurized 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 volume of hydrogen is required to supply the same amount of energy. Therefore, maintaining the security of supply is more challenging in hydrogen networks, and hence linepack (Dragoni 2017; Amiryar and Pullen 2017) 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.) As presented in (Taylor et al. 2012) in the Iron Mains Replacement Programme, the existing low pressure gas distribution pipes are being converted from iron to plastic for health and safety reasons. This new distribution gas infrastructure will be able to transport hydrogen within districts (over short distances). On the other hand, new pipelines for hydrogen transmission at national level are likely to be required.

In hydrogen transport, key challenges are: (a) delivery cost, (b) energy efficiency, (c) linepack management, (d) maintaining hydrogen purity, and (e) minimizing hydrogen leakage (Smallbone et al. 2017). Hence, by taking into account the challenges and obstacles in sustainable production, transport, storage, distribution, and safety (Hedlund et al. 2015), currently a global hydrogen-based economy is not considered feasible unless an appropriate storage medium could be established. For direct large-scale hydrogen storage, mediums such as salt caverns (Yulong et al. 2017) and hydrides (Crabtree et al. 2015) has been investigated, however there are still many challenges from techno-economic perspective. Consequently, alternative carbon-free fuels such as ammonia (NH_3), which stores hydrogen (comprises 17.8% of hydrogen by mass (May et al. 2018) without involving the carbon molecule, may become more attractive (May et al. 2018; Kumar et al. 2017).

6.4.4.2 *Ammonia: Promising Hydrogen Energy Carrier*

Ammonia is produced most commonly through the Haber and Bosch process by the catalytic reaction of nitrogen and hydrogen (Delmas 2018). Liquid ammonia has recently been considered as a highly capable hydrogen carrier (Staffell and Rustomji 2016; Schmidt et al. 2017b; Nykvist and Nilsson 2015) due to its high gravimetric and volumetric hydrogen storage (Staffell and Rustomji 2016). The energy density of ammonia is 38% higher than liquid hydrogen (Gur 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 fertilizers (approximately 80%), followed by many industrial processes such as refrigeration, petrochemicals, and food processing (Hammond and Hazeldine 2015). Ammonia production and transport are established industrial processes (∼180 mtonnes/year (Janek and Zeier 2016)), and hence ammonia is considered to be a scalable and cost-effective fuel source. The life cycle assessment (LCA) of ammonia production methods through fossil fuels is demonstrated in (Van Noorden 2014). If ammonia is produced from biomass (gasification), the GHG emissions is 0.38 kg CO_2 eq./kg NH_3, while from natural gas (SMR method) and coal (gasification) it is 3.03 and 3.85 kg CO_2 eq./kg NH_3, respectively.

In Figure 6.25, an overview of the production, transportation, and utilization of hydrogen and ammonia for energy purposes is presented. As presented, ammonia can be produced from Renewable Energy Resources (RES) (Blomgren 2017) and fossil fuels, while current hydrogen and ammonia production processes are mainly reliant on fossil fuels (Hwang et al. 2017), which is associated with carbon emissions.

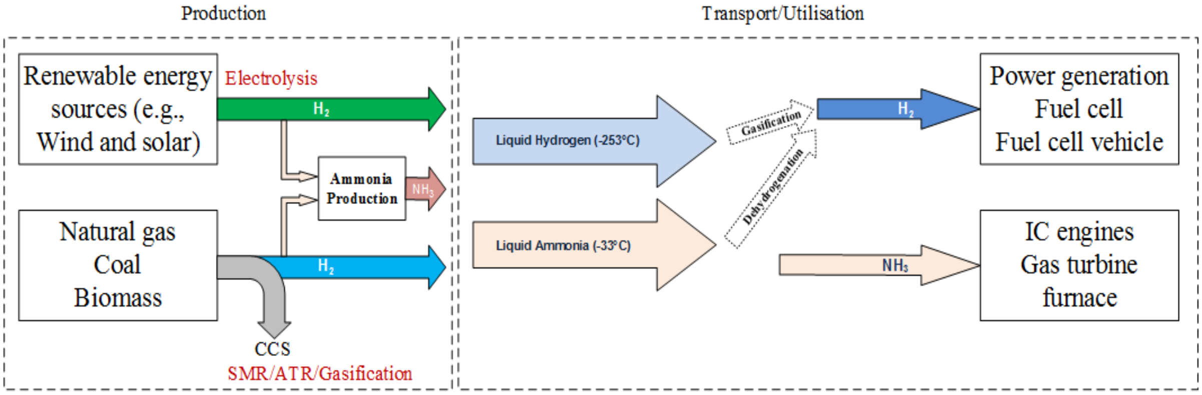


Figure 6.25 Ammonia and hydrogen production, transport and utilisation

As it is demonstrated in Figure 6.25, hydrogen, similar to natural gas, can be liquefied in order to be transported at volume via sea and without pressurization, while liquefying hydrogen (LH_2) requires temperature of -253ºC and is therefore energy-intensive, and hence increasing the cost of transport (Smallbone et al. 2017; Kolpak and Grossman 2011). 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 (Lin et al. 2017b).

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 Liquefied Natural Gas (LNG) or LH_2 (Janek and Zeier 2016). There is currently energy loss of about 15-25% when cracking ammonia back into hydrogen (Gonzalez et al. 2016; Wang et al. 2017a; Matos et al. 2019), which could favour the use of ammonia, rather than hydrogen in certain sectors. A project where ammonia could be exported from Saudi Arabia to Japan is also under consideration (Amirante et al. 2017).

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 (Arenas et al. 2019; Navalpotro et al. 2017). A project is under development in Brunei to export hydrogen to Japan using LOHCs (Arenas et al. 2018).

Hydrogen should be gasified to be used or injected into the pipelines. On the other hand, ammonia can be used directly as a fuel without any phase change for internal combustion (IC) engines, gas turbines, and furnaces. 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 (Janek and Zeier 2016). 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 RES along with ammonia energy recovery technologies could play a major role in forming an ammonia economy (IRENA 2017). The combustion process of ammonia is very similar to natural gas in gas turbines. However, due to low flammability of ammonia (Barbour et al. 2016), there are difficulties in the ignition as well as burning velocity compared to other fuels. Many studies such as (Highview Power 2019; Sarbu and Sebarchievici 2018; Xu et al. 2014) investigated the role of the ignition mechanism control, which through the existing technologies, emission will be produced (Xu et al. 2014; Kempener and Borden 2015). The 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) (Körner et al. 2015). 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, since the existing technologies are mainly developed for hydrocarbon fuels.

6.4.4.3 *Challenges around hydrogen energy fuels*

All these energy carriers need to resolve safety issues around flammability, toxicity and safe storage of medium in order to be viable options for transporting, storing hydrogen at scale (Hedlund et al. 2015). Particularly, beside the GHG emissions in the LCA of hydrogen energy carriers, a key challenge in use of ammonia is NO_x emissions (released from nitrogen and oxygen combustion) and unburned ammonia, which are directly toxic. To deal with NO_x emissions, a special catalyst would be adapted to combine ammonia with nitrogen to decrease the nitrogen oxides production (Körner et al. 2015). Due to low flammability of hydrogen (He and Wang 2018) and ammonia (Barbour et al. 2016), a stable combustion in the existing gas turbines is not feasible. In this regard, as an example, Siemens (Tessier et al. 2016) has successfully increased the percentage of hydrogen that can be used in gas turbines and stated that further development of gas turbines would enable operation of 100% hydrogen by 2030 (Tessier et al. 2016).

To deal with the GHG emissions (e.g., in LCA of ammonia and hydrogen), there is a potential to use advanced feedstocks such as microalgae, which has the ability to fix the atmospheric carbon by capturing the CO_2. Additionally, it has numerous advantages including high productivity, no arable land requirements, and potential to grow in diverse water quality and climates (Gallo et al. 2016a). Moreover, by carrying out different chemical pathways such as hydrothermal and supercritical water gasification different energy carriers such as hydrogen can be produced from algae. However, currently there are limitations in employing these approaches/concepts in commercial contexts, and this requires further research and development of new technologies.

6.4.4.4 *Electricity Transmission*

The efficiency of renewable resources vary significantly across regions and continents. For example, the energy intensity of the wind resource is large in the North of Europe while solar resource is large in the South of Europe (Figure 6.26). In this context, electricity transmission infrastructure could facilitate cost effective deployment of renewable generation. More generally, the case for increased electricity interconnection across different countries and regions rests on three core benefits: (i) enhanced the security of supply, (ii) enhanced operation efficiency and (iii) more cost-effective deployment of renewables. 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 plants needed to meet security of supply requirements. Hence, the diurnal and seasonal characteristics of different renewable energy source such as wind and PV should be considered in optimising the generation and network design and therefore maximising the asset utilisation to support the integration of renewable technologies.

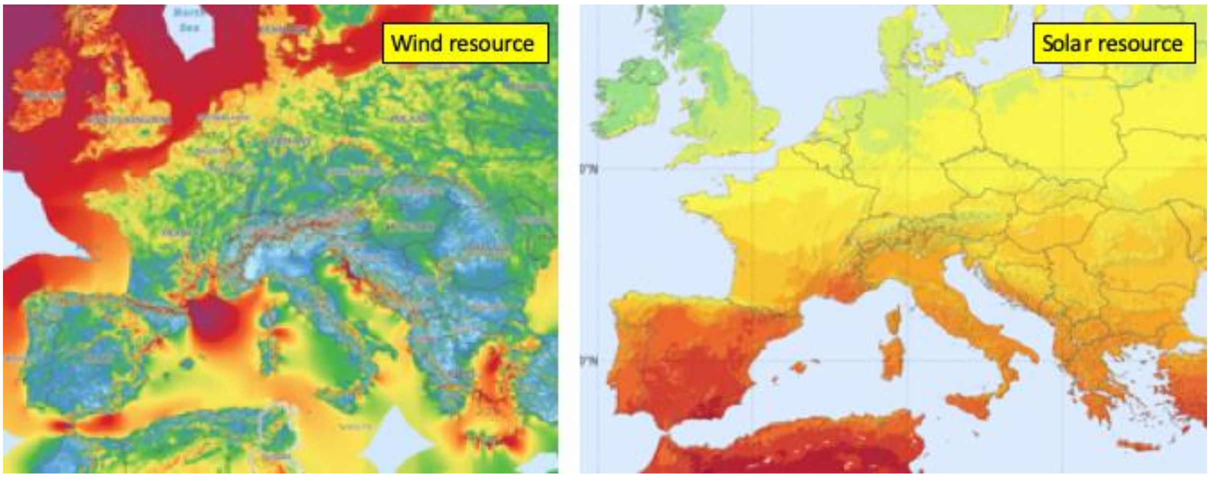


Figure 6.26 Spatial intensity of the wind (Global Wind Atlas 2019) and solar (Global Solar Atlas 2019) power resources in Europe.

For example, the analysis provided in (Dijkstra et al. 2012; Pudjianto et al. 2013) demonstrates that solar production in southern Europe is dominant in summer while wind generation in northern Europe is more significant in winter, which would make regional/continental approach of decarbonisation cost-effective. During winter, high wind output and low PV output, the grid can facilitate the North to South flows while during summer, the flows would reverse.

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. This could save more than €150bn of capital expenditure by 2030 (Newbery et al. 2013). Although the cost of renewables continues to decline, it will still be important to consider the benefits of regional deployment strategies. 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. Also, the development of transmission infrastructure that would provide access to very strong solar resources in the Sahara Desert could significantly reduce the cost of energy system decarbonisation in Europe. As scenario analysis demonstrates, 15% of Europe's electricity demand could be supplied from solar farms (PV and Concentrated Solar Power) located in the Sahara Desert. 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.

In the context of transmission network design, there is a roughly even split between Alternated Current (AC) and Direct Current (DC) technologies, with AC being used mostly in Overhead-Head Lines and DC in underground/undersea cable. In terms of route length, AC transmission corridors are typically shorter than 200km, strengthening cross-border links and connecting generation and load regions over long distances. These operate at standard high voltages (HV) in the region of 400 kV rather than Ultra high voltages (UHV) at 800 kV and above. The State Grid Corporation of China is building a 1.1 million volt transmission line (12 GW capacity) that will be able to transport electricity over 2,000 miles (Technology). This project is the first of its kind in the world, and a major step towards the development of international and intercontinental mega-grids.

HVAC and HVDC technologies are well-established and widely used for bulk power transmission (Cole and Belmans 2009). HVDC is used with underground cables or long-distance overhead lines where HVAC is infeasible or not economic (Rao S 2013; Lazaridis 2005). VSC-HVDC (voltage-source converter HVDC) is growing in voltage level, power rating and efficiency, which makes it increasingly competitive to the conventional CSC-HVDC (current-source converter HVDC) technology due to its advantages in controllability in weak grids, reliability, and ability to facilitate bi-directional power flows (in turn a facilitator of multi-terminal systems). However, VSC-HVDC are characterised by larger power losses in the converter stations, and somewhat lower maximum ratings, than CSC-HVDC. This provided incentives to further develop VSC technology to drive down losses so that its other benefits may be more widely accessed. An alternative approach would be to enhance the controllability of CSC technology to make it more suited to weak-gird conditions and allow its high ratings to be exploited more widely. A third approach is some form of hybridisation that combines the controllability of VSC with high rating and low power loss of VSC.

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) (Ruddy et al. 2016; Fischer et al. 2012; Ngo et al. 2016) and half-wave AC (HWACT) transmission (Prabhakara et al. 1969; Prabhakara 1969). 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). Similarly, HWACT has not yet been demonstrated at scale, 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 (CIGRE 2017; Chaffey 2016), improvement in cabling technology, including the use of superconductors and nanocomposites (Ballarino et al. 2016). A number of DC circuit breaker designs have been proposed, and some tested at scale, but not yet being deployed.

In addition, there are also 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. 2014b). 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 2016).

Optimizing the designs and operations of the interconnected transmission system, both onshore and offshore grids, also requires more integrated economic and reliability approach (Moreno et al. 2012) to ensure the optimal balance between the economics and the provision of system security while maximizing the benefits of smart network technologies. 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 and Strbac 2009). All of these factors, including the risk associated with future uncertainty, should be considered in designing and operating offshore networks or long-transmission systems in order to derive strategic decisions and maximize the long-term benefits and utilization of the network investment (Du 2009; Strbac et al. 2014).

In this context, market design, infrastructure regulation and policy framework related to the development of regional interconnections should be aligned with decarbonization agenda, which is currently the core barrier for cost effective deployment of renewable generation (Newbery et al. 2013).

6.4.5 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 (de Coninck et al. 2018; Mundaca et al. 2019). Most importantly, end users, including consumers, businesses and industry, need to adopt relevant mitigation options, and then use these in the intended way (Steg et al. 2015; Stern et al. 2016). Moreover, the implementation of mitigation options, such as wind parks, CCS, hydropower plants and nuclear power plants, may be inhibited when these options are not acceptable to actors (Perlaviciute et al. 2018).

- End users can engage in a wide range of actions that would reduce carbon emissions in energy systems (Abrahamse et al. 2007; Dietz 2013; Creutzig et al. 2018; Hackmann et al. 2014; Grubler et al. 2018). This includes the following options. People can use renewable energy sources with low carbon emissions. They can produce 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.
- End users can also adopt technologies that support variations in energy supplies, for example, facilitating optimal use of variable renewable energy production. This reduces 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. Technology can also be installed to store energy (e.g., batteries and electric vehicles) or to automatically shift on or off appliances (e.g., fridges, washing machines), depending on the availability of renewable energy.
- End users can adopt energy-efficient appliances and systems, and increase the resource efficiency of end uses – for example by insulating buildings, constructing passive or energy positive buildings, and using low carbon building materials – so that less energy is required to provide the same service.
- End users can change their behaviour to reduce overall energy demand or to match energy demand to available energy supplies. For example, they can adjust room temperature settings, reduce showering time, use mass transit rather than fly or drive, or operate appliances such as washing machines or tumble dryers when renewable energy production is high.
- End users can 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 the products (e.g., buying local products). Similarly, they can engage in behaviour 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.

Identifying enablers and barriers for these mitigation actions is critical to understand how relevant actions can be facilitated and encouraged. Many factors shape whether mitigation options are feasible and considered by end users, including contextual factors, individual abilities, and different types of motivation to engage in behavior.

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 & Griffith, in press), low carbon diets (Dubois et al. 2019), and advanced fuel choices (Van Der Kroon et al. 2013). Moreover, uptake of PV is higher when financial conditions are favourable (Wolske and Stern 2018a), good facilities increase recycling (Geiger et al. 2019), and vegetarian meal sales increase when more vegetarian options are offered (Garnett et al. 2019)(Garnett and Pilling 2019).

Mitigation actions are more likely when individuals feel capable to adopt them (Geiger et al. 2019; Pisano and Lubell 2017), 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; Wolske and Stern 2018b; Chang et al. 2009). Yet, higher income groups can afford more carbon-intensive lifestyles (Abrahamse et al. 2007; Namazkhan et al. 2019; Brandon and Lewis 1999; Frederiks et al. 2015). 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 (Hornsey et al. 2016) (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 are considered and prioritised when making choices. People who strongly value protecting the environment and other people are generally 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 maximize self-interest, which implies that they consider different types of costs and benefits when making choices. Specifically, they not only consider individual, but also affective, social, and environmental costs and benefits.

- People are more likely to engage in mitigation behaviour (i.e., energy saving behaviour, investments in energy efficiency, resource efficiency in buildings, renewable energy generation), when they believe individual benefits of such behaviour exceed individual costs (Harland et al. 1999; Steg and Vlek 2009; Kastner and Matthies 2016; Kastner and Stern 2015; Korcaj et al. 2015; Kardooni et al. 2016; Wolske et al. 2017), including financial benefits, convenience, comfort, autonomy and independence in energy supply (Wolske and Stern 2018a). Yet, individual costs and benefits seem less important than people generally assume. For example, financial consequences seem less important for decisions to invest in energy-efficiency and renewable energy production than people indicate (Zhao et al. 2012).
- People are more likely to engage in mitigation behaviors when they expect to derive positive rather than negative feelings from such actions (Smith et al. 1994; Pelletier et al. 1998; Steg 2005; Carrus et al. 2008) Brosch et al. 2014; (Pelletier et al. 1998; Taufik et al. 2016). Such positive feelings may be elicited when behaviour is pleasurable, but also when behaviour is perceived as meaningful (Bolderdijk et al. 2013b; Taufik et al. 2015).
- Social costs and benefits can affect climate action (Farrow et al. 2017), although people do not always recognize 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 ((Harland et al. 1999; Nolan et al. 2008; Rai et al. 2016). 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). Further, individuals may engage in mitigation actions when they think this would signal something positive about them to self and others (Griskevicius et al. 2010; Milinski et al. 2006; Noppers et al. 2014; Kastner and Stern 2015). Social influence can also originate from political and business leaders (Bouman and Steg 2019); GHG emissions are lower when legislators have strong environmental records ((Jensen and Spoon 2011; Dietz et al. 2015).
- 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 other 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 generally motivated to mitigate climate change. The more individuals are aware of the environmental impact of their

behaviour, 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), engaged in the initial behaviour for environmental reasons (Peters et al. 2018), and when initial actions make them realise they are a pro-environmental person, motivating them to engage in other mitigation actions so as to be consistent (van der Werff et al. 2014; Lacasse 2015, 2016). This suggests it would be important to create conditions that make it likely that initial mitigation actions motivate further actions.

6.4.6 Systems and System Integration

The energy system is undergoing fundamental transformation in response to tightening energy sector decarbonisation targets. Delivering on this transformation will require a significant increase in the provision of system-wide flexibility, enabled by deployment of innovative technologies and advanced control systems that would support evolution to the digitalised energy paradigm (Lund et al. 2015; Nicolosi 2010; Shakoor et al. 2017). There are two fundamental effects responsible for the additional system costs that are associated with the low carbon agenda:

One effect is reduced efficiency of system operation; that is, the need for balancing services will increase significantly above historical levels at high penetration of variable renewable generation. An absence of flexibility will reduce the ability of the system to accommodate variable renewable and base-load nuclear generation, leading to curtailment of renewable output. Increased curtailment would compromise ability to transition to low-carbon energy systems and significantly increase overall system cost. Hence, the future energy system will require new sources, technologies and control systems to provide flexibility.

The other effect is degradation in the utilisation of energy infrastructure; that is, intermittent renewable generation will displace the energy produced by conventional fossil-fuel plants, but its ability to displace the capacity of the conventional plant will be very limited. Furthermore, the electrification of segments of the heat and transport sector represents a major challenge as the increase in peak demand may be disproportionally higher than the corresponding increase in energy. The surge in peak demand will potentially require very significant reinforcement of the generation and network infrastructures.

6.4.6.1 *Role and value of flexibility technologies and advanced control systems*

System flexibility is the ability to adjust generation or consumption in the presence of system constraints to maintain a secure system operation to energy users. System flexibility will be a key enabler of this transformation to a cost-effective low-carbon energy system. There are several flexibility resource options available including highly flexible thermal generation, energy storage, demand-side response, and cross-border interconnection to other systems (Lannoye et al. 2012; Cochran et al. 2014a; Lannoye et al. 2011). System flexibility has two-time dimensions: (i) an operational dimension, which is associated with the use of resources, both energy and ancillary services, to ensure efficient and secure system operation (Ulbig and Andersson 2015; Brouwer et al. 2015); and (ii) a capacity dimension, which is associated with maintaining the long-term capacity requirement of the system (Ma et al. 2013; Lannoye et al. 2015). The two dimensions of flexibility are complementary to each other. For example, energy storage supports maintaining demand-supply balance during system operation, and it can also reduce a system's peak demand lowering the need for generation and network capacity in the long-term. Technologies and control systems that can provide system flexibility can be classified into five main categories.

- *Flexible generation*: advances in conventional generation technologies are allowing them to provide enhanced flexibility to the system. This is due to their ability to start more quickly, operate at lower levels of power output (minimum stable generation), and achieve faster changes in output (Strbac et al. 2015).

- *Cross-border interconnection*: interconnectors to other systems enable large-scale sharing of energy, ancillary service and back-up resources (Pudjianto et al. 2014a).
- *Demand Side Response (DSR):* DSR schemes can re-distribute consumption and engage demand-side resources for system balancing to enhance system flexibility without compromising the service quality delivered to end customers (Arteconi and Polonara 2018; Heinen and O'Malley 2019; D'hulst et al. 2015). These schemes have a very significant potential to provide different types of flexibility services across multiple time frames and system sectors, from providing primary frequency response to facilitating network congestion management. Distributed generation, smart appliances, electric vehicles and energy storage technologies will transform passive consumers into active prosumers that may provide both energy and flexibility services to both local and national systems, with no compromise on service quality delivered to consumers.
- *Energy storage*: energy storage technologies have the ability to act as both demand and generation sources. They can contribute substantially to services such as system balancing, various ancillary services and network management (Pudjianto et al. 2014a; Arteconi and Polonara 2018; Heinen and O'Malley 2019; Zhang et al. 2018a).
- *Integrated cross-sector energy system operation:* this can provide significant flexibility through optimising the interactions between electricity, heating /cooling, transport and gas sectors, and considerably reduce system integration cost of renewable generation (Bai et al. 2015; Stephen and Pierluigi 2016).

By exploiting new sources of flexibility, there is the potential to realise cost savings relative to a system that continues to rely on conventional generation to deliver flexibility. The corresponding savings are associated with:

- *Efficient provision of operating reserve and response facilities*: the provision of operating reserve to the system by non-thermal flexibility technologies (i.e. storage, DSR and interconnection, cross-vector flexibility) increases the ability of the system to absorb low-carbon electricity and reduces the need to maintain thermal plant with associated impacts on carbon emissions and operating costs due to efficiency losses.
- *Potential savings in generation capacity*: new service providers may reduce overall generation capacity on the system due to one of two factors. Reduced need for low-carbon capacity in the system: The presence of system flexibility sources such as energy storage facilities demand-side response or interconnectors can absorb/export surplus generation in the system thus avoiding energy curtailment and associated costs (Bouffard and Ortega-Vazquez 2011; Pavić and Capuder 2016). For example, this analysis demonstrates that in the UK case, the carbon targets could be met by building 14 GW less nuclear or 20GW less offshore wind generation (Sanders et al. 2016). Reduced need for back-up capacity: system flexibility in the form of energy storage or demand side response can reduce system peak which combined with interconnection, can reduce the amount of required generation capacity in the system (particularly peaking plant capacity).
- *Deferral or avoidance of network reinforcement/addition*: in addition to the network capacity savings driven by lower generation capacity requirements (as described above), additional network capacity savings are possible by deploying flexibility to manage network constraints and reassessing the need for network reinforcement in conjunction with innovative network planning and operation standards.

This constitutes a paradigm shift from the traditional redundancy in an asset-based approach to the use of intelligence for providing resilience and security in future electricity systems. A range of studies has been carried out to model the integrated electricity-heat-gas-transport system and investigate the overall benefits achieved through the interactions across different energy vectors (pre-heating, thermal storage, DSR, smart charging of EVs, Vehicle to Grid - V2G, etc), which will significantly reduce the cost of decarbonisation (Mancarella 2009; Fang et al. 2012; Li et al. 2017; Zhang et al. 2018b, 2019; Aunedi et al. 2016; Fischer et al. 2017; Blarke and Lund 2007; Nuytten et al. 2013; Lund et al. 2010; Chua et al. 2010; Heinen et al. 2016; Klein et al. 2014; Lane 2017; Strbac et al. 2018a; Ameli et al. 2017; Qadrdan et al. 2017; Clegg and Mancarella 2016; Mancarella and Chicco 2013; Martinez Cesena and Mancarella 2019; S and Mancarella 2018; Strbac et al. 2018b; Hedegaard et al. 2012; Hast et al. 2017; Meibom and Kiviluoma 2010; Li et al. 2016; Lin et al. 2017a). This evolution of the historical electricity system structure to future smartly integrated low carbon energy system, is presented in Figure 6.7.

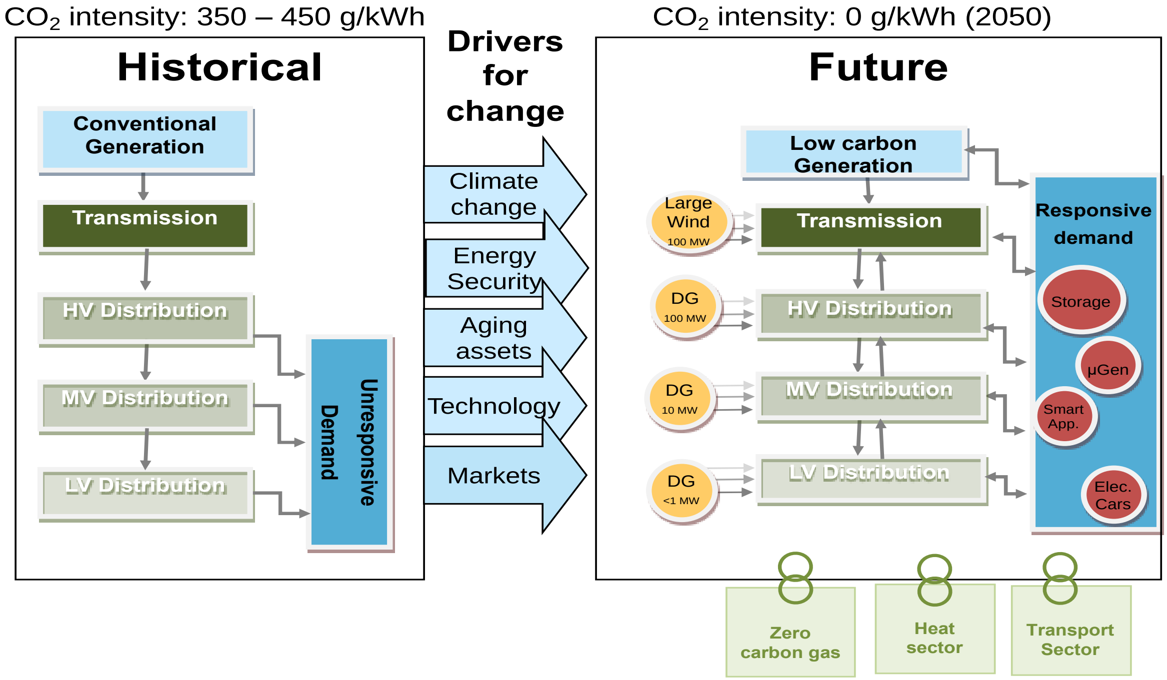


Figure 6.27 Transition to future smartly integrated low carbon energy system

Cross-vector integrated approaches to the design and operation of future energy system can provide significant benefits. For example, thermal storage (Hedegaard et al. 2012; Hast et al. 2017; Meibom and Kiviluoma 2010) and preheating (Li et al. 2016; Lin et al. 2017a) can provide significant flexibility to the electricity system as it can shift thermal loads to off-peak periods, reducing the overall system capacity requirement, improving the utilisation of renewables, and reducing operating costs.

Analysis demonstrates that flexibility technologies and advanced control of integrated multi-vector energy systems would reduce the total cost of investment in energy generation and network infrastructure in low carbon energy systems for more than 25%.

6.4.6.2 *Cost effective integration of variable renewable energy sources*

Future low-carbon energy systems will most likely involve high penetration of variable wind and solar renewable generation technologies, which will impose challenges for system integration. The key components of *System Integration Costs* (SIC) of renewable generation include:

- *Increased balancing cost* associated with a) increased requirements for system reserves due to higher uncertainty of variable renewable generation output, and b) increased requirements for frequency regulation due to reduced system inertia;
- *Network reinforcements costs* related cost of upgrade of interconnection, transmission and distribution network infrastructure;
- *Backup capacity cost* due to limited ability of variable renewable technologies to displace “firm” generation capacity needed to ensure adequacy of supply;

- *Cost of maintaining system carbon emissions*, reflecting the requirements to reduce the carbon emissions.

Flexibility technologies and advanced control systems will facilitate cost effective integration of variable renewables (Aunedi et al. 2016; Zhang et al. 2019). As demonstrated in the figure below, system integration costs of wind and solar generation greatly depend on the system flexibility as well as on the overall penetration levels (example based on UK and EU studies). Note that the *Whole System Costs* (WSC) of renewables are equal to the sum of *Levelized Cost of Energy* (LCOE) and *System Integration Cost* (SIC); (WSC=LCOE+SIC).

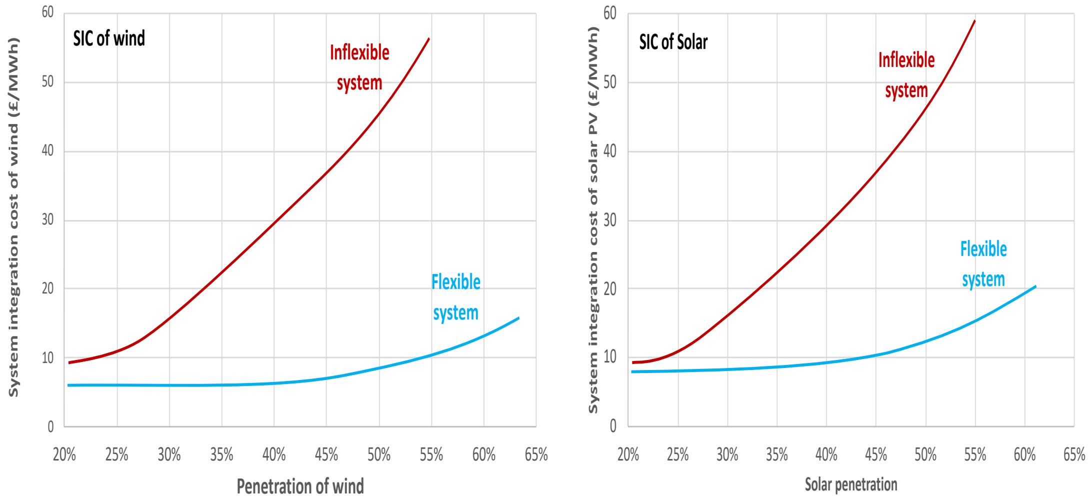


Figure 6.28 System Integration Cost (SIC) of wind and solar in inflexible and flexible systems, as a function of the penetration level of renewable generation

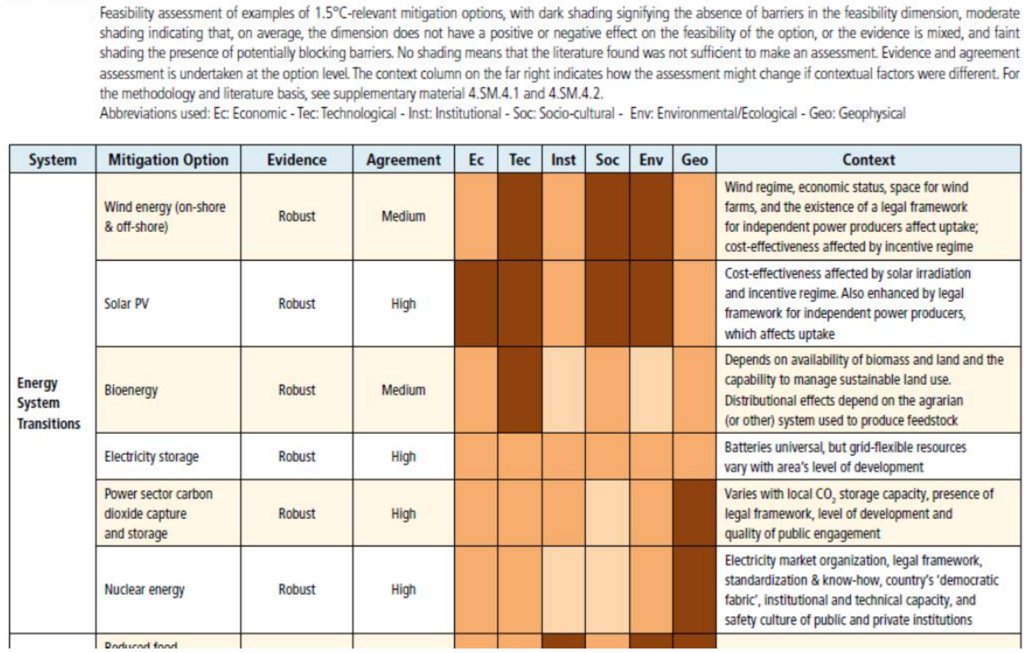
In the inflexible system, when the penetration of renewable generation increases beyond 50%, system integration costs would be above £50/MWh, which could make the whole-system costs of renewable generation higher than other low carbon generation, such as Nuclear and Carbon Capture Utilisation and Storage (CCUS). System flexibility reduces system integration cost of renewable generation significantly (as penetration level increases), which considerably enhances the competitiveness of renewable generation. Note that the minimum system integration cost is between £7-£9/MWh, as in this case renewables cannot provide security of supply and backup plant will be needed (given the conservative assumption that during extreme peak demand conditions there would be very limited output from renewables for several days).

Going towards zero carbon energy system, integration costs of renewables could increase significantly, indicating that significant capacity of firm low carbon generation (e.g. nuclear) will be required. Alternatively, the utilisation of renewable energy sources could be enhanced through use of long-term energy storage (LTES) to store excess renewable output over longer time horizons (Xu et al. 2014; Gabrielli et al. 2017), that would support large scale deployment of variable renewable sources. There are a number of LTES technologies such as underground thermal energy storage, seasonal pit heat storages, salt hydrate technology, phase-change materials, hydrogen storage etc. The benefit and value of LTES technologies in enabling the use of more variable and lower cost RES instead of higher-cost but firm low-carbon generation such as nuclear or CCUS has also been (Strbac et al. 2018b). For example, production of hydrogen by electrolysers ("Power-to-Gas") that would be then be used to produce electricity by hydrogen-based power generation when required. This also will require significant longer term storage of hydrogen. Energy in the form of hydrogen/ammonia can be stored across long time horizons as losses are minor and not time dependent. Electrolysers can also provide balancing services during high RES output and therefore reduce the need for these services from other sources. In this context, LTES would make 100% renewable generation based energy system feasible.

6.4.7 Summary of Mitigation Options

[Placeholder for SOD-This section is under construction. It will include two tables or similar graphic concepts: (1) a table indicating the “feasibility” or desirability of different options along the dimensions articulated in the introduction to 6.4 and (2) a table with some important technology cost and performance information.]

Table 6.15 Summary of the feasibility or desirability of different mitigation options. Dark shading signifies the absence of barriers, moderate shading indicates that, on average, the dimension does not have a positive or negative effect on the feasibility or desirability of the options, or the evidence is mixed, and faint shading indicates the presence of potentially blocking barriers. [Placeholder from the SR15 – will be updated for the second-order draft.]



Feasibility assessment of examples of 1.5°C-relevant mitigation options, with dark shading signifying the absence of barriers in the feasibility dimension, moderate shading indicating that, on average, the dimension does not have a positive or negative effect on the feasibility of the option, or the evidence is mixed, and faint shading the presence of potentially blocking barriers. No shading means that the literature found was not sufficient to make an assessment. Evidence and agreement assessment is undertaken at the option level. The context column on the far right indicates how the assessment might change if contextual factors were different. For the methodology and literature basis, see supplementary material 4.SM.4.1 and 4.SM.4.2.
Abbreviations used: Ec: Economic - Tec: Technological - Inst: Institutional - Soc: Socio-cultural - Env: Environmental/Ecological - Geo: Geophysical

System	Mitigation Option	Evidence	Agreement	Ec	Tec	Inst	Soc	Env	Geo	Context
Energy System Transitions	Wind energy (on-shore & off-shore)	Robust	Medium	▨	■	▨	■	■	▨	Wind regime, economic status, space for wind farms, and the existence of a legal framework for independent power producers affect uptake; cost-effectiveness affected by incentive regime
	Solar PV	Robust	High	■	■	▨	■	■	▨	Cost-effectiveness affected by solar irradiation and incentive regime. Also enhanced by legal framework for independent power producers, which affects uptake
	Bioenergy	Robust	Medium	▨	■	□	▨	□	▨	Depends on availability of biomass and land and the capability to manage sustainable land use. Distributional effects depend on the agrarian (or other) system used to produce feedstock
	Electricity storage	Robust	High	▨	▨	▨	▨	▨	▨	Batteries universal, but grid-flexible resources vary with area’s level of development
	Power sector carbon dioxide capture and storage	Robust	High	▨	▨	▨	□	▨	■	Varies with local CO_2 storage capacity, presence of legal framework, level of development and quality of public engagement
	Nuclear energy	Robust	High	▨	▨	□	□	▨	■	Electricity market organization, legal framework, standardization & know-how, country’s ‘democratic fabric’, institutional and technical capacity, and safety culture of public and private institutions
	Reduced food			▨	▨	■	▨	■	■	

Table 6.8 Summary of cost and performance characteristics of key energy technologies.

[Placeholder for SOD- under development. What is shown here is just a quick sample of some of the levelized cost information we have gathered to date.]

Technology	Levelized Cost of Electricity ($/MWh)		
	2019	2030	2050
Solar PV	41.7-111.6	38.5-100.8	13.4-77.5
Wind	28-54	21-41	17.2-33.4
Hydroelectric	41.7-58.3	39.0-48.1	38.8-86.8
Biomass	92.3-120.2	80.7-112.1	74.2-106.8
Biomass with CCS	106.5-260.1	93.1-242.6	85.7-231.1
Geothermal	69-112	37.2-45.2	34.5-41.5
Coal	66-152	68-93	66.0-91.0
Coal with 30% CCS	131-132	92.5-138.2	89.1-185.2
Coal with 90% CCS	91-124	87.0-110.6	81.5-113.0
Gas combined cycle	44-68	37-52	39.0-65.7
Gas combined cycle with CCS	65-69	64-83	64-95.4
Nuclear	89.3-91.9	73.6-79.4	69.3-74.7

Note: Based on the average annual growth rate from 2030 and 2040, we calculate the LCOE in 2050. The cost of BECCS is 15.4%-116.4% higher than Biomass technology in the base year, and by this ratio we calculate LCOE of BECCS in 2030 and 2050. Source: Energiewende (2015); BENF (2015); Berg (2016); Fisher (2016); NREL (2018); LAZARD (2019); EIA (2019).

6.5 Climate Impacts on the Energy System

Climate change mitigation will depend in large part on the ability to transform the energy system. However, components of the energy system are also affected by a changing climate, through long-term changes in climate parameters (e.g. temperature and precipitation), climate variability (e.g. inter and intra-annual variability) and the occurrence of extreme weather events (Cronin et al. 2018). These impacts are not limited to the supplies of renewable energy, which are often weather dependent, but can affect various aspects of the power system.

The climate impacts on the energy systems can be classified in three general areas: (1) the effects of climate change on renewable energy production through direct changes to geophysical potentials (e.g. more or less clouds that affect the solar radiation; changes in temperature, precipitation, and CO_2 concentrations that affect bioenergy production), (2) changes to the overall structure and operation of the electric power system (e.g. through changes in the seasonality of solar and wind power production), and (3) changes in the vulnerability of the electric power system to extreme weather events (e.g. temperature effect on power line ampacity). The various time scales of the changes in the energy system climate change do not occur in isolation. For example, faults in electricity transmission due to lightning (very-short time scale) can occur in the context of extreme heat waves (weekly to monthly time scale), which are already occurring on top of climate change (long-term changes). The occurrence of extreme weather events is linked to the system adequacy. An event can be very rare, but it can be very expensive to increase the system adequacy to minimize risks. These three general areas are discussed below.

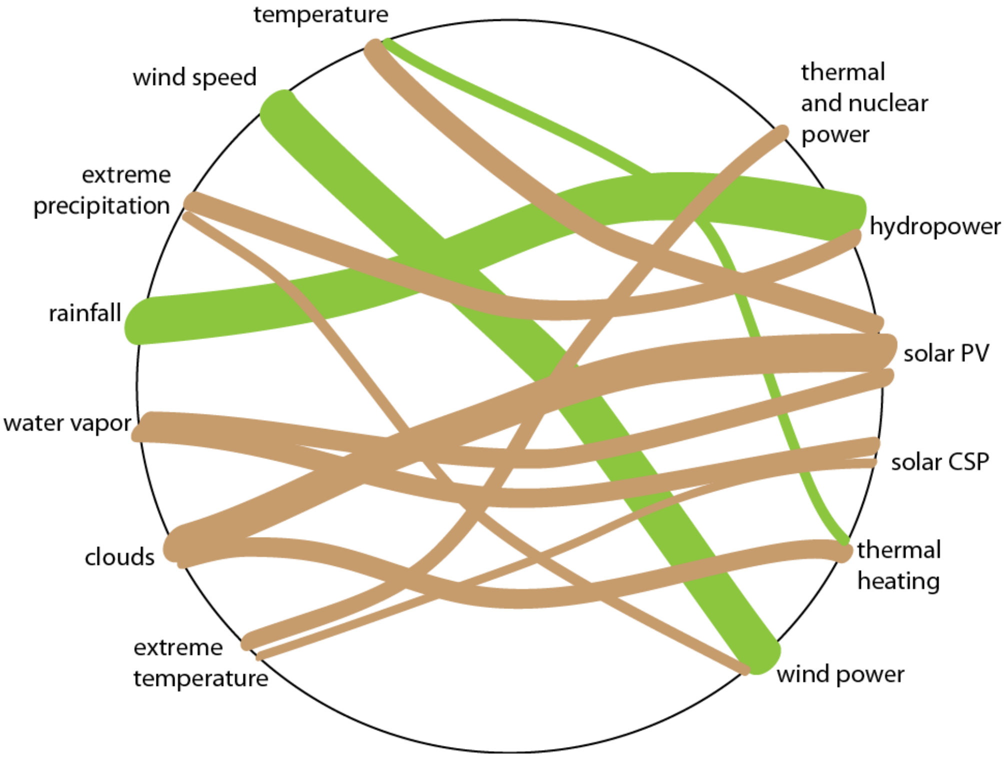


Figure 6.29 Schematic representation of the effect of changes in various climate parameters (left) on energy generation (right). Green lines represent positive effect, brown lines represent negative effects. The width of the line represents the importance of the parameter. [Placeholder for SOD-A new more developed figure will be available in the second-order draft].

6.5.1 Impacts on Renewable Energy Supplies

Weather- and climate-dependent renewable energy sources are potentially sensitive to climate change (see summary in Figure 6.). Studies that approach this issue from a global perspective are few, however. In general, effects are expected to increase with the level of disruption to the current climate system, but the nature and magnitude of these effects are technology-dependent and somewhat uncertain, and they may vary substantially on regional and local levels (Bruckner et al. 2014). Hydro, wind, solar and ocean power generation can be strongly affected by climate change at the local and regional scale. Bioenergy production, through climate, vegetation growth, and the human management of agriculture and land-use relationships, as well as feedback is also potentially very sensitive to climate change.

6.5.1.1 *Hydropower*

General Circulation Model (GCM) studies suggest an intensification of the hydrologic cycle (i.e. CMIP5 models in AR5/GWI on average project a gradual increase in global precipitation over the 21st century) as warming global temperatures increase the rate of evaporation worldwide (IPCC 2013).

The production of hydropower is directly related to the availability of water, and hydropower plants are designed in accordance to it. Changes in overall 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 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. Increased runoff and changes in seasonality require adaptation in the hydropower station management and may require security upgrades. Extreme weather jeopardizes structure security that needs to be taken into account on the production (IHA 2019; Schaeffer et al. 2012). Decreased runoff can reduce hydropower production due to decrease in water availability as well as increase water conflict among different economic activities such as agriculture (Mereu et al. 2016), and water and energy demanding industry (Fan et al. 2019). Climate change can also lead to higher air temperature leading to surface evaporation and reduction of water storage, to changing in timing of snow and ice melt, and to loss of equipment efficiency (Ebinger and Vergara, 2010; Mukheibir 2013; Fluixá-Sanmartín et al., 2018). Climate change can also alter the demands for water use by other sectors which can affect the availability of water for hydropower generation (Solaun and Cerdá, 2017; Spalding-Fecher et al., 2014).

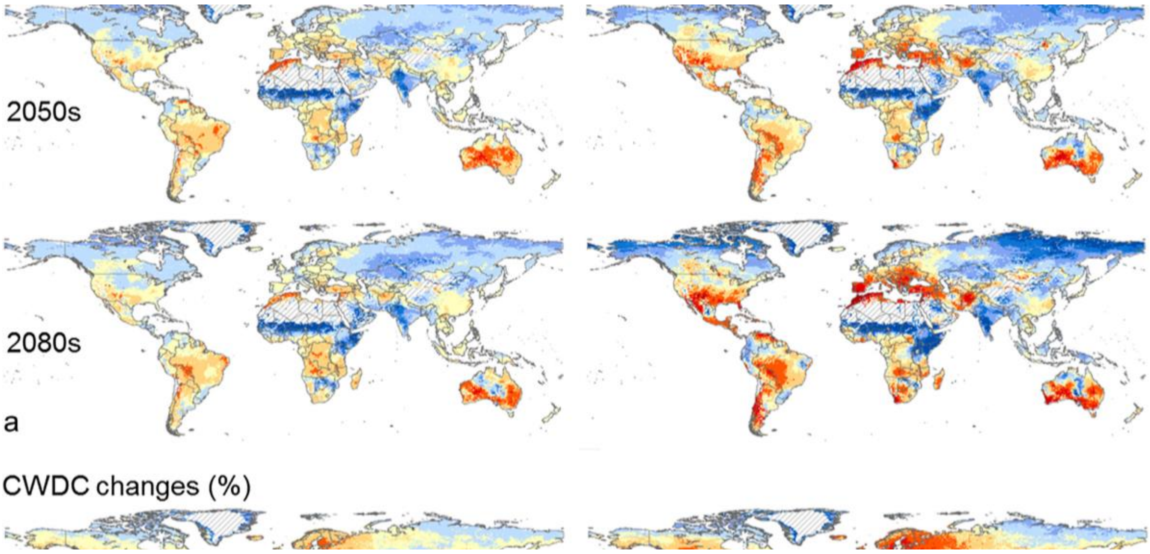


Figure 6.30 Global spatial patterns of changes in gross hydropower potential based on climate forcing from five GCMs. Changes are shown for the 2050s (upper) and the 2080s (lower) for RCP2.6 (left) and RCP8.5 (right) scenarios relative to the control period (1971–2000). [This figure is from (Van Vliet et al. 2016a), Figure 5].

Although climate change may affect hydropower in a number of ways, most studies have focused on how changes in river flow would affect hydropower potential (Cronin et al. 2018; Schaeffer et al. 2012)(Solaun and Cerda 2019). The conclusions regarding climate change impacts on hydropower vary due to differences in modelling assumptions and methodology, such as choice of the Global Circulation Model (GCMs), 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 (Van Vliet et al. 2016a) Turner et al., 2017). Nonetheless, the analyses are consistent in demonstrating long-term impacts from climate change on hydropower potential.

(Van Vliet et al. 2016a) show decreases in gross global hydropower potential between –0.4% (GCM-GHM ensemble mean for RCP 2.6) and –6.1% (RCP 8.5) for the 2080s compared to 1971–2000 (Figure 6.30). Other studies (Turner et al 2017), suggest more modest changes at the global scale, but stronger regional changes, with 5–20% increases for most areas in high latitudes (Van Vliet et al. 2016a) Turner et al. 2017) and decreases by 5–20% in other areas connected with increased drought conditions (Cronin et al. 2018). Globally, 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. 2016a,b). (Hamududu and Killingtveit 2012), on the other hand, show mild changes in both global and regional impacts on hydropower generations. The results of the three latest mentioned works are consistent in that they indicate 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. They are also consistent in indicating a decrease in the USA, central and southern Europe, Middle East, central Asia and Southern South America. These studies are, however, in disagreement regarding hydropower production in China, central South America, and partially in Southern Africa.

There is a recent move towards small hydropower stations, with no or small reservoirs associated to them. These stations are considered more sustainable if compared to large ones due to their smaller environmental impact. This tendency, however, raises a new challenge for the future, as small hydropower stations are most vulnerable to changes in runoff and thus to future climate change.

6.5.1.2 *Wind Energy*

Global wind energy potentials are not expected to substantially change under future climate potentials (Pryor and Barthelmie 2010); however, studies have indicated consistent shifts in the geographic position of the lower atmospheric jets under RCP 8.5 (Harvey et al. 2014). (Karnauskas et al. 2018) finds decreases in wind power across the Northern Hemisphere mid-latitudes and increases across the tropics and Southern Hemisphere, with substantial regional variations. Variations in the models in reproducing resources and extreme components of the wind distributions have been identified (Pryor and Barthelmie 2013), which may increase uncertainty in resource assessment under climate change. With newer studies, the spread in mean wind speeds in Europe and North America by the end of the century has been revised up (Cronin et al. 2018), with differences in wind energy density reaching up to +30% in the Baltic regions and –30% in Eastern Europe (Carvalho et al. 2017). Many regional studies exist for example for Europe (Moemken et al. 2018; Carvalho et al. 2017; Devis et al. 2018), but most do not to take into account the fine-scale dependence of wind power on the topography and wind direction (Sanz-Rodrigo et al 2017), or the effect of expanding wind energy extraction on local and regional climate (Lundquist et al. 2019). Increasing extreme wind speeds due to climate change have been identified for some regions (Pes et al. 2017; Pryor and Barthelmie 2013). 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).

6.5.1.3 *Solar Energy*

Climate change projections (i.e. CMIP5 comprehensive set of global climate 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. Here all-sky radiation increases by about 0.3 $W/m^2/year$. In higher latitudes, all-sky radiation trends are negative (–0.5 $W/m^2/year$) which coincide with positive cloud cover trends, which are increasing by about 0.05%/year. Some of these trends reflect changes in pollution levels in the CMIP5 scenarios. For example, in India, (Ruosteenoja et al. 2019) in a multimodel-mean response study, shows that radiation diminishes by 0.5%–4% by the period 2030–59 (relative to 1971–2000), in tandem with strengthening aerosol and water vapor dimming. The largest reduction is anticipated for northern India.

Increases in downward solar radiation, however, will often be counterbalanced by decreasing efficiency due to rising surface air temperatures, which show significant increases in all models and scenarios. A first order estimate of the impact of solar radiation and temperature changes in (Wild et al. 2015) indicated statistically significant decreases in PV outputs in large parts of the world under the RCP 8.5 scenario, but notable exceptions with positive trends in large parts of Europe, South-East of North America and the South-East of China.

In terms of CSP, a complementary article (Wild et al. 2017) found a potential for future increases in CSP production in many parts of the globe, with few exceptions such as the North of India previously mentioned. In contrast to PV, CSP output increases with increasing temperatures, which adds to the increasing solar radiation projected by the CMIP5 models for some regions. Compared to the changes in PV production, the estimated future production changes by CSP are larger by a factor of 4 (Wild et al. 2017).

When regional analyses are carried out, significant discrepancies among models emerge. Multi-model means of RCMs show trends in surface solar radiation of –0.60 W/m^2 per decade 2006–2100 over Europe (Bartók et al. 2017). Solar PV supply by the end of this century compared with the estimations made under current climate conditions should be in the range (–14%; +2%), 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. These calculations include the impact of solar radiation, and other variables affecting the PV panel efficiency such as surface air temperature and surface wind speed.

6.5.1.4 *Ocean Energy*

Wave resource is potentially affected by changes in water temperature, temperature gradients, salinity, sea level and wind patterns (Solaun and Cerda, 2019); however, very few studies exist. (Reguero et al. 2019) shows increases in wave power globally since 1948, and also expected to increase in the future. There are also possible relationships between sea level change and tidal renewable energy (Pickering et al 2017) and also in the positions and intensity of tidal mixing fronts (Souza 2013), which will affect the optimal location for tidal energy installations.

6.5.1.5 *Bioenergy*

[Placeholder for SOD-This section will be substantially expanded for the SOD. The text here is only a placeholder. The next version will review the results from statistical analysis of changing crop yields as well as the results from crop models.] Research has consistently demonstrated that climate change will have a meaningful effect on the yields of agricultural products, including bioenergy. Increased temperature, changes in precipitation, and rising CO_2 concentrations will all influence agricultural and bioenergy yields. These changes will arise not only from the long-term evolution of climate; they will also be affected by shorter-dynamics such as floods and droughts. While warming has positive impacts on bioenergy, food requirements for a growing world population strongly influence bioenergy potentials (Haberl et al. 2011).

6.5.2 Impacts on the Electric Power System Structure and Operations

Climate change will affect the energy system in a number of ways beyond overall changes in the supply of renewable energy resources. One implication is the structure and operation of future, low-carbon electric power systems heavily-dependent on solar and wind power. The feasibility of these systems is an important topic in the context of climate mitigation (Heard et al. 2017; Brown et al. 2018; Zappa et al. 2019; Jacobson et al. 2017) (see box in Section 6.6). The models reviewed or used in these assessments are highly complex and thus many simplifications and assumptions are made (Brown et al. 2018), which increases their uncertainty. In general, few of the 100% renewable power system assessments consider how climate change can affect the availability and variability of low-carbon supply options (Fisher-Vanden et al. 2013) and the impacts of extreme weather events under climate change scenarios have been less extensively studied than gradual ones (Cronin et al. 2018). This is especially important because high penetration of wind and solar power in the grid increases the dependence of the power supply on weather and climate conditions (Jerez et al. 2019; Craig et al. 2019). For example, (Van Der Wiel et al. 2019) analysed the occurrence of extreme low renewable energy production and extreme high energy shortfall events in Europe in two ensemble GCM simulations and concluded that projected changes due to long-term climate change are substantially smaller than interannual variability. They also noted that these high-impact events are of large scale and spatial redistribution of wind turbines and solar panels cannot prevent them. In addition to the changes in the resources discussed in Section 6.5.1, climate change can change the spatiotemporal dependencies in wind and solar generation. In (Carvalho et al. 2017), wind generation is projected to decrease mainly in summer and autumn, with generation in winter expected to increase northern-central Europe and a decrease in the southernmost Europe.

Climate change can also affect electricity generation from thermal power plants, including nuclear power, geothermal power, and fossil and bioenergy with CCUS. Hotter air and water temperatures can both lead to lower production from these facilities. Droughts decrease potential cooling water for these facilities or raise the possibility of water outlet temperatures exceeding regulatory limits, leading to lower production or even shutdowns.

Climate change will also influence electricity demand. These changes will take place on both long-term and shorter timescales. Studies have consistently shown that heating demands will be lower and cooling demands will be higher. These countervailing effects generally balance overall energy demands in regions with both heating and cooling, whereas energy demands increase in regions primarily in need of cooling, and the opposite is true in regions dependent largely on heating. At the same time, because heating and cooling take place at different times of year, these effects do not balance one another at any single point in time. In one U.S. case study (Fonseca et al., 2019), total electricity consumption increased on average by 20% during summer months, while during winter it decreases by the end of the century. Changes in loads may result in changes in the typical generation dispatch patterns. A study in the USA shows that 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 (Auffhammer et al. 2017). As electrification can also change the load patterns, the combined effect of climate change and sector coupling can be expected.

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 and network infrastructure, while global warming is likely to reduce the efficiency of thermoelectric generation, with possible impacts also on renewable sources such as wind. Rising sea levels may pose significant risks to coastal or riverside power system infrastructure. It is recognized that these risks compound in a complex way and the corresponding impacts and severity are not fully understood. To the extent that climate change affects these factors, it may have important impacts on power system vulnerabilities.

6.5.3.1 *Climate and Weather Threats to Power Systems*

Extreme weather and storms manifest as threat vectors to power systems through various different ways, which affect system resilience, reliability, and adequacy. Corresponding to power system security, these terms can be understood as the ability of the power system to provide power to customers as required given different operational conditions.

High wind speeds can shear wind lines through mechanical failure, or cause lines to collide with each other causing transient events. High wind speed shutdown can affect the output of wind power plants over a period of minutes as storm fronts move (Macdonald et al. 2014). This can happen over longer periods of time and large regions with transmission, distribution, and generation infrastructure affected (Jamieson et al. 2019) concurrently. Short-term or hourly variations in weather conditions can also have significant ‘ramping’ effects on the net output of wind turbines across the system (Sorensen et al. 2007), necessitating rapid changes in generation dispatch to retain system stability and security (Dawkins 2019).

Vegetation also presents a risk to overhead lines during extreme wind events due to falling branches and debris, which can cause transients, or collapsing trees which can sever lines or collapse poles and towers (Kuntz et al. 2002). Furthermore, wildfires also are increasingly threats during dry periods in warmer climates which can affect wide areas of the power system, driven by wind and having the potential to do catastrophic damage both to the electrical system and wider society (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 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.

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 has also the potential of increasing the probability of lightning-related events.

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). Such outages can contribute to cascading events. These are problematic as they impact large areas of network simultaneously and particularly lines at high altitudes, which can be challenging to reach in adverse weather conditions to perform system repairs. Snow, sleet, and blizzard faults can also be associated with overhead line faults when they coincide with high wind conditions (Murray and Bell 2014). Snow, sleet, and blizzard faults can also be associated with overhead line faults when they coincide with high wind conditions (Murray and Bell 2014). This is because the snow or ice increases the mechanical load on the lines concurrent with increased lateral loading associated with wind forces.

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. Restoration can be particularly challenging, as assets will be difficult to reach during adverse weather conditions of this nature. *Heat* can pose a risk to power system equipment. 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.

Thermal effects influence electricity load profiles, as mentioned in section 6.5.2. Ambient temperatures can also significantly affect the generation portfolio available. *Droughts* can affect the supply of hydropower and thermoelectric generation (Van Vliet et al. 2016b). Water availability affects hydro generation and cooling water availability affects thermoelectric (e.g., nuclear and fossil-fueled) generation (Koch et al 2014). (Van Vliet et al. 2016a) shows significant reduction in hydroelectric utilisation during acutely hot or drought years – with utilisation falling by 5.2% for hydroelectric and 3.8% of thermoelectric generation. This was primarily associated with water shortage. Similarly, increasing ambient temperatures will mean reduced generator efficiencies due to the manner of operation of thermal engines (De Sa and Al Zubaidy 2011). Solar heat faults occur under conditions of high temperatures and low wind speeds and can be exacerbated by the urban heat island (McColl et al 2012). Wildfires also are increasingly threating during dry periods in warmer climates which can affect wide areas of the power system, driven by wind and having the potential to do catastrophic damage both to the electrical system and wider society (Dian et al. 2019).

6.5.3.2 *Climate Change and Vulnerability of Power Systems*

The effect of climate change on power system vulnerability will depend on the degree to which climate alters the frequency and intensity of extreme weather events as well as longer term climatological phenomena. While weather can have an important influence on power system vulnerability, climate change will only alter this vulnerability to the extent that it alters these weather patterns and the occurrence of extreme events.

As presented in sections 6.5.1.2 and 6.5.2, climate change can affect wind energy resources, likelihoods of very high wind speeds and the spatiotemporal dependencies in wind. Higher maximum wind speeds can increase the high wind speed related threats to power systems described in section 6.5.3.1. In windy scenarios, the system may simultaneously be experiencing high demand at a time lines are particularly at-risk from mechanical failure from wind and storm related effects. Extreme events such as Hurricane Katrina are capable of devastating entire networks concurrently with flooding and precipitation, with large sections of network heavily damaged for extended periods of time (Entriken and Lordan 2012).

Climate change can change the probability of lightning-related events, as there is physically more energy in the atmosphere. Romps et al (2014) predicts an increase in the frequency of lightning events in USA due to an increase in convective available potential energy. This suggests an associated change in risk of flashover events, overloads, and wildfires linked to lightning strikes. In McColl et al (2012), impacts of climate change on several threats have been assessed for the UK power system. The likelihood of lightning-related faults is projected to increase in the future. The solar heat fault likelihood is projected to increase. The conditions that cause flooding faults may increase in the future, but a reduction cannot be ruled out. No clear signal associated with the future frequency of wind and gale faults was found. Due to reduction in the number of snow days, sleet and blizzard faults are projected to decrease. 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). Given the links with 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 with both transient threats associated with electrical faults due to lightning strikes on power system assets increasing, and damage associated with fires and common-mode faults linked to vegetation failures on lines also at risk of increase globally.

Climate change may affect system adequacy by reducing electric transmission capacity due to increasing temperatures (Bartos et al 2016). If there is significant air conditioning load in the system, the reduced transmission capacity and peak summertime load increase due to climate change can have a combined impact of reducing system adequacy. The review in (Cronin et al. 2018) show that while many papers refer to increasing damage to energy infrastructure due to storms (high wind speeds, floods, landslides), only a few studies were found to quantify these.

Rising temperatures are expected to reduce power plant output due to reduced thermal efficiencies (Cronin et al. 2018). Reduced water resources impact cooling water availability for power stations. Significant possible impact of climate change is reported in Koch et al (2014), where the analysis show that for some power plants, e.g. those located in the Rhine basin, the electricity generation is shut down completely because of too high water temperatures. This shows potentially significant impact of climate change on power system adequacy in the future.

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 defence 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.

Box 6.12 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 2012). 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 (Taha 2013, Ma et al 2017). In the regional scale, modelling studies have shown the same effects, thus 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 (2015) 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 (Zhou et al 2012, 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 (e.g. Vautard et al 2014, Wang et al 2019). 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 2019). 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 Carbon-Neutral Energy Systems

6.6.1 What is a Carbon-Neutral Energy System?

Limiting temperature change to 1.5°C, 2°C, or even 3°C ultimately requires GHG reductions toward, at, or beyond zero, which includes attaining at least net zero global CO_2 and declining non-CO_2 radiative forcing (IPCC 2018a). Policies, investments, and other actions today will determine the speed at which countries are able to create energy systems that produce little or no GHG emissions or that might remove emissions from the atmosphere. Some actions may speed progress, while other actions will hinder the transformation and reduce the possibility of limiting temperature change below 2°C or 1.5°C. An understanding of these future energy systems is valuable to chart a course toward them over the coming decades.

This section synthesizes current understanding of carbon-neutral energy systems. The subsequent section (Section 6.7) discusses pathways toward these low-emissions energy futures. The motivating questions for the section are as follows. (1) What are the different types of carbon-neutral energy systems? (2) What are the key characteristics of these systems and where are there flexibilities? (3) Which types of systems would be most appropriate for which countries?

Box 6.13 Ways of defining future energy systems

Multiple different terms have been used to describe future energy systems, including carbon-neutral and low-carbon. These terms are often muddled and overlapping. Three that are of interest here include

“Climate-neutral” energy systems are energy systems associated with zero net economy-wide CO_2 emissions to the atmosphere. Energy emissions may be above, at, or below zero depending on the degree of CO_2 emissions or uptake from non-energy systems, for example, from non-energy CDR or uptake by terrestrial systems.

Carbon neutral energy systems are energy systems that produce no carbon on net, sometimes also called “net zero energy systems”.

Low-carbon energy systems are energy systems with carbon footprints well below those of today. While definition and time horizons vary, generally numbers such as 50% or 80% reduction in annual greenhouse gas emission by 2030 or 2050 are used in the literature.

A useful starting point is to consider energy systems associated with net zero CO_2 levels across the whole economy, which we refer to as “climate-neutral” energy systems. The net zero, economy-wide CO_2 framing has become increasingly salient in long-term planning. Discussions surrounding efforts to limit temperature change to 1.5 °C or 2 °C are now frequently communicated based on the point at which net anthropogenic CO_2 emissions reach zero, accompanied by substantial reductions in non-CO_2 emissions (IPCC 2018a). This economy-wide CO_2 goal also appears in many mid-century strategies, though it is used in a variety of ways. Most existing climate-neutrality commitments from countries and subnational jurisdictions aim for economies with very low emissions but are far from zero, as offsets, CDR methods, and/or land sink assumptions are used to achieve net-zero goals.

A precise description of a climate-neutral 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. Net global CO_2 emissions are the gross amount emitted from human activity less anthropogenic CDR. These emissions might take place within the energy sector or outside the energy sector, notably through land-use change emissions. Similarly, CDR might be deployed within our outside of the energy sector (), although many CDR options, such as direct air capture, would be important energy users. Energy systems that utilize BECCS may remove GHGs from the atmosphere. In other cases, if CDR methods are deployed outside of the energy system (e.g., direct air capture, net negative agriculture, forestry, and land use CO_2 emissions), it is possible for the energy system to still emit GHGs even while economy-wide emissions are zero or below.

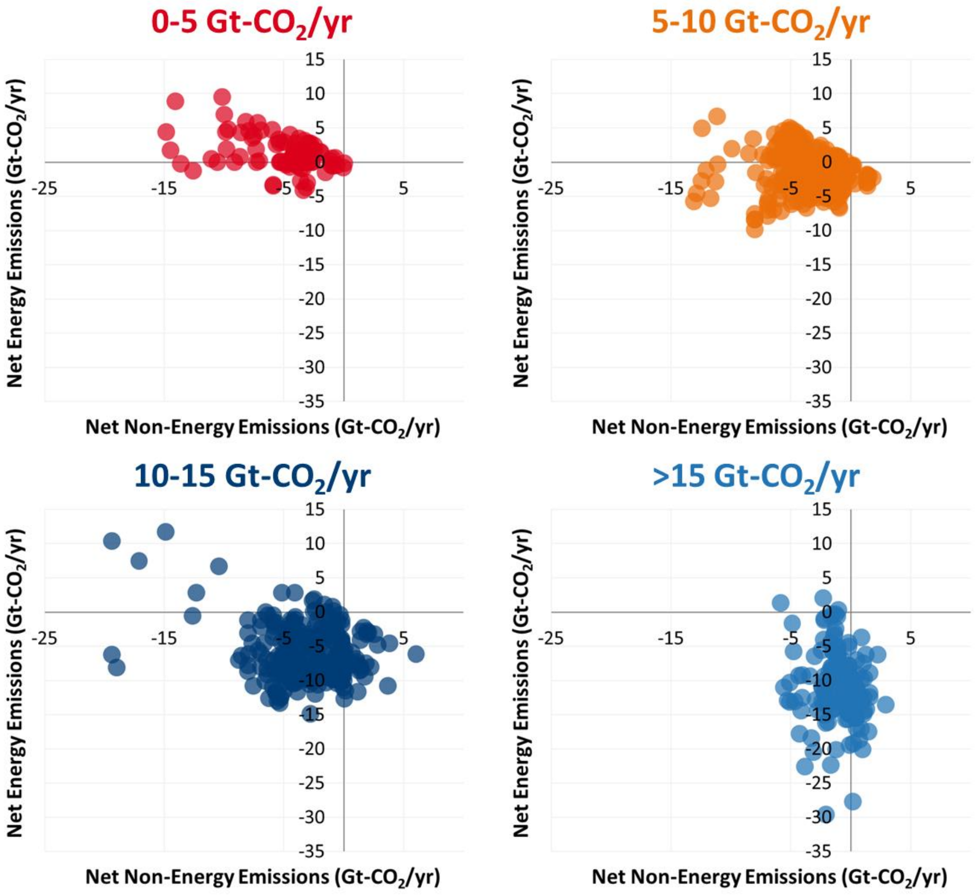


Figure 6.31 Total net global annual CO_2 emissions (including energy, industrial processes, and non-energy) and net non-energy emissions for all scenarios and years with net-zero total CO_2 emissions (IPCC 2018a). Points represent separate models and scenarios, which are color-coded by the amount of energy CDR.

Within the energy system, the demand for and availability of CDR has an important impact on the degree to which the energy system is a source of negative emissions. CDR in the energy system can lead to net-negative energy sector emissions and/or it can be used to neutralize residual emissions from hard-to-decarbonize sources.

For the purposes of the assessment in this section, we focus on energy systems that produce zero net CO_2 emissions; that is, carbon-neutral energy systems. While these systems may not correspond directly to the point at which overall economy-wide CO_2 emissions reach zero (that is, "climate-neutral" energy systems), 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 carbon-neutral energy systems is not discussed in this section.

6.6.2 Configurations of Carbon-Neutral Energy Systems

Carbon-neutral energy systems could involve a range of configurations. Although many mitigation options have alternatives, there is a finite number of technological choices for each functional role in the system, which entail tradeoffs across economic, environmental, and social dimensions (Davis et al. 2018). 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. Many socioeconomic, policy, and market uncertainties will also influence the configuration of carbon-neutral energy systems (van Vuuren et al. 2018; Krey et al. 2019; Bistline and Young 2019; Smith et al. 2016a). 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 climate-neutral energy systems are still speculative and have not been clearly explicated in country-specific pledges or in the 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 for the transition toward climate-neutral energy systems. Analysis has focused on identifying potential decarbonization technologies and pathways for different sectors, enumerating opportunities and barriers for each, highlighting robust insights, and characterizing key uncertainties (Hepburn et al. 2019; Davis et al. 2018). Each future system faces challenges with cost, scalability, public acceptance, and interactions with other parts of the energy system, and many considerations will determine the feasibility and outlook for each.

The literature on carbon-neutral energy systems is limited. On the one hand, there is a robust integrated assessment literature that provides snapshots of these systems in very broad strokes (AR6 database). All integrated assessment scenarios that pass through zero energy sector CO_2 emissions provide high-level snapshots of those systems. However, because these snapshots operate at a very high level, they do not consider the complexities of the many system interactions, infrastructure needs, associated scaling challenges, and societal factors that could ultimately influence what system might be most appropriate for any country. 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 carbon-neutral energy systems, most notably decarbonized electricity systems (see 6.6.2.2 below).

Box 6.14 Archetypes of Carbon-Neutral Energy Systems

The possible configurations of carbon-neutral energy systems are limitless. At the same time, there are several key dimensions that can be valuable in articulating the overall character of these systems and providing insights for planning and strategy. Key dimensions include, but are not limited to, energy demand per capita or per unit of economic output, the degree of CDR in the energy system, the primary energy sources (e.g., solar, wind, nuclear, bioenergy with or without CCS, fossil energy with or without CCS). Depending on long-term goals, near-term climate policy, and demand, illustrative climate-neutral energy system archetypes can be constructed to highlight different features of possible systems. These archetypes are high-level and necessarily gloss over the many details associated with these systems, but they nonetheless provide a high-level sense of the possibilities.

- A configuration with limited use of energy sector CDR, supplied largely with renewable energy, and based on relatively lower energy per capita.

- A configuration with limited use of energy sector CDR, supplied by a broader variety of supply sources and with relatively higher energy per capita.

- A configuration with substantial energy-sector CDR, supplied by a variety of energy sources, and with moderate energy demand.

- A configuration with substantial energy-sector CDR, supplied by a variety of energy sources, with moderate energy demand, and providing negative overall energy-sector emissions.

[Placeholder for SOD-In the next version of this document, we will pull actual examples of several carbon-neutral energy systems from the integrated assessment literature, long-term strategy literature, and official MCSs. We will develop a consistent set of quantitative metrics/charts along with a short qualitative description to describe each.]

While the literature on carbon-neutral energy systems is diverse, it is also true that a number of common characteristics emerge from across the space of existing literature. We focus on the ones those common characteristics in the remainder of this subsection.

Box 6.15 Common Characteristics of Carbon-Neutral Energy Systems

Although there is no single possible configuration for climate-neutral energy systems, there are a number of characteristics of these systems that can be found across scenarios in the literature. Seven of these are as follows:

- Limited and targeted use of fossil fuels
- Zero or negative CO2 emissions from electricity
- Widespread electrification of end uses
- Alternative fuels in hard-to-decarbonize 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

Robust Conclusions. Virtually all climate-neutral energy systems in the literature use far less fossil fuels than today. The precise quantity of used will depend upon the relative costs of such fuels, electrification, and most importantly, the degree of CDR in the energy system. The quantity of fossil fuels used in the future depends upon the combined costs of such fuels and compensating carbon management (e.g., CDR, CCS) relative to non-fossil sources of fuels. For most applications, it seems likely that making fossil fuels climate-neutral will be more expensive than either climate-neutral electrification or use of non-fossil sources of fuels, but there may be residual demand for fossil petroleum and gas given their high energy density. Future demand for coal is likely to be very low.

Flexibilities and Uncertainties. There is considerable flexibility regarding the overall quantity of liquid and gaseous fuels that will be required in carbon-neutral energy systems. 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 such fuels that are fossil or fossil-derived is uncertain, and will depend on the feasibility of CCS and CDR technologies and long-term sequestration as compared to climate-neutral fuels. Moreover, to the extent there are physical, biological, and/or socio-political limits to carbon management, non-energy emissions may be even more challenging to avoid. Indeed, such competition might favor non-fossil sources of fuels.

6.6.2.2 Zero or Negative CO_2 Emissions from Electricity

Robust Conclusions. Because there are so many lower-cost options for producing zero-carbon electricity, decarbonized or net-negative-emissions electricity systems are robust characteristics of carbon-neutral energy systems (AR6 database; (Barron et al. 2018; Krey et al. 2014a)). These lower costs and the range of available electrotechnologies to provide residential, commercial, transport, and industrial energy services make the electrification of end uses another robust characteristic, which can influence total electricity demand, hourly load shapes, and system flexibility needs and impel changes in the supply-side mix (Williams et al. 2012; EPRI 2019a) (see 6.6.2.2 below).

Flexibilities and Uncertainties. There is a great deal of variation in the possible mix of zero- or net-negative-emissions power systems. These systems will entail a mix of renewables, dispatchable ("on-demand") low-carbon generation (e.g., nuclear, CCS), energy storage, transmission, and demand management (Bistline et al. 2018; Jenkins et al. 2018b; Luderer et al. 2017; Macdonald et al. 2016). We can expect variable renewable energy to produce a larger proportion on average than it does today, but that does not imply that entirely renewable energy systems will be desirable under all conditions, as economic and operational challenges increase sharply as shares approach 100 percent (Bistline and Young 2019; Shaner et al. 2018; Bistline 2017; Gowrisankaran et al. 2016; Frew et al. 2016). There are debates about how much wind and solar can be brought onto the system and what mechanisms would need to be in place to be able to manage variability. Either dispatchable generation or seasonal energy storage are used to ensure reliability and resource adequacy in high wind and solar scenarios, though each option involves uncertainty about costs, timing, and public acceptance (Sepulveda et al. 2018).

There are many substitute technologies for different functional roles in low-emitting power systems, and deployment of these resources will be influenced by the evolution of technological costs, system value, and resource endowments (Veers et al. 2019; Mai et al. 2018; Bistline et al. 2018; Hirth 2015; Fell and Linn 2013). The precise mix of power sector technologies will likely vary by country and region depending endogenous resources, on the aforementioned considerations and by difficult-to-model factors like human capital, related industrial bases, and societal preferences (O'Neill et al. 2017).

Energy storage is expected to play a large role, especially in systems with high variable renewable energy, but the extent of deployment varies based on the system value for different technologies (Arbabzadeh et al. 2019; Denholm and Mai 2019; Balducci et al. 2018). For instance, diurnal storage options like lithium-ion batteries have different value propositions than storing and discharging electricity over longer periods with less frequent cycling, which require different technologies, supporting policies, and business models (Gallo et al. 2016b). Carbon capture, utilization, and storage 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.

Maintaining reliability will increasingly entail system planning and operations to account for characteristics of supply- and demand-side resources at higher levels of spatial and temporal resolution (Hu et al. 2018). Markets with more granular price signals can enhance efficiency and reliability (Ela et al. 2014). 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 (EPRI 2018). Given the variation in regional resources and system variability, there may be considerable economic and technical advantages to greater coordination across jurisdictions, sectors, and levels of government (Bistline et al. 2019; Chan et al. 2018; Konstantelos et al. 2017).

The approach to difficult-to-decarbonize sectors (see Section 6.6.2.4) could impact power sector planning. A major question is whether negative emissions technologies like bioenergy with CCS will be included in the electricity mix if, for instance, aviation decarbonization is too difficult, costly, or delayed (Luderer et al. 2018; Bauer et al. 2018; Mac Dowell et al. 2017). BECCS could displace other low- to zero-carbon options like wind, solar, and nuclear. If non-energy CDR options are pursued instead of BECCS, land-use implications could impact electric sector planning given differences in spatial considerations for alternate power system mixes (Van Vuuren et al. 2017a). Additionally, if direct air capture technologies are used as part of a climate-neutral energy system, electricity and heat requirements could impact asset utilization (Realmonte et al. 2019). Ultimately, the long-lived nature of assets and lag time associated with R&D make near-term activities important for meeting longer-term goals and for setting the course toward the long-run power sector mix in carbon-neutral energy systems.

Box 6.16 Renewables integration in carbon-neutral energy systems

As countries consider potential future carbon-neutral energy systems, an important question that arises is the proportion of wind and solar energy that can be included in the power system. There are many grids with high renewable shares and large anticipated roles for variable renewables, primarily wind and solar, in future low-carbon power systems (Cochran et al. 2014b). Renewables integration involves technical and economic challenges due to unique characteristics of wind and solar such as their spatial and temporal variability, short- and long-term uncertainty, and non-synchronous generation (Cole et al. 2017). For instance, uncertainties with weather-dependent wind and solar output create forecast errors that can impact power plant commitment and dispatch decisions and operating reserves to support reliable system operations (Ela et al. 2017, 2014). To manage these issues, studies indicate roles for larger installed system capacity, expanded transmission and balancing area size, and increased flexibility in both generation and load responsiveness, among other approaches (Jenkins et al. 2018b; Mai et al. 2018; Milligan et al. 2015). Technical and economic integration challenges depend on system specifics and renewable deployment levels. Although there are debates about how much wind and solar is economic under different conditions and which mechanisms would be desirable to facilitate integration (Bistline and Young 2019), studies illustrate the technical feasibility of using renewables to meet hourly electricity demand under a range of conditions (Zappa et al. 2019; Cochran et al. 2014b).

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

- **Energy storage:** Energy storage technologies like batteries, pumped hydro, and hydrogen can provide a range of system services (Balducci et al. 2018). Batteries have received attention as costs fall and installations increase, but very high renewable shares entail either dispatchable generation or seasonal storage to ensure reliability and resource adequacy (Arbabzadeh et al. 2019; Jenkins et al. 2018b). In addition to providing energy and capacity, 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 2019b; Castillo and Gayme 2014).
- **Transmission and trade:** To balance spatial 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 flows (Bistline et al. 2019; 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 like gas with lower minimum load levels (Bistline 2019; Denholm et al. 2018), other renewables like hydropower or biomass (Hirth 2016), or flexible nuclear (Jenkins et al. 2018a). The composition depends on cost and simultaneous policy goals, though in all cases, generation from these resources falls faster than their capacity as renewable shares increase (Bistline 2017).
- **Demand management:** Many low-emitting and high-renewables systems also utilize increased load flexibility in the forms of energy efficiency, demand response, and demand flexibility (Imelda et al. 2018; Hale 2017; Merrick et al. 2018). Despite the assumed availability of these resources in many modeling applications to facilitate renewable integration, the potential levels of demand management that consumers would be able and willing to provide is uncertain.

Deployment of these integration options will depend on their relative costs and value, and considerable uncertainty exists about future technology costs, performance, availability, scalability, and public acceptance (Kondziella and Bruckner 2016; Bistline and Young 2019). The use and deployment of balancing resources likely requires operational, market design, and other institutional changes, as well as technological ones in some cases (Cochran, et al. 2014). The mix will differ regionally based on resources, system size, and whether the grid is isolated or interconnected. Although there are no inherent limitations on the maximum renewable penetration on a grid, the economic value of additional wind and solar capacity decreases as their penetration rises, which creates economic challenges at higher deployment levels (Wiser et al. 2017; Gowrisankaran et al. 2016; Hirth 2013). The integration options mentioned above can mitigate these value declines but likely do not solve them, especially since these technologies can exhibit decreasing returns themselves (Denholm and Mai 2019; Bistline 2017; De Sisternes et al. 2016).

Scenarios with 100% renewable electricity systems are emerging in the literature e.g., (Jacobson et al. 2015) however, some of these studies have generated controversy for their input assumptions, model simplifications, and framing (e.g., (Clack et al. 2017)). Deep decarbonization analyses, including multi-model comparison studies with detailed models of power sector investments and operations, indicate large roles for variable renewables, but least-cost pathways for meeting emissions reduction targets rarely suggest near 100% wind and solar mixes unless optimistic assumptions about integration challenges are combined with pessimistic assumptions about alternatives (Jenkins et al. 2018b; Bistline et al. 2018). Although many studies find 100% renewable systems technically conceivable, economic and operational challenges increase sharply as shares approach 100 percent, though there is disagreement about the magnitude of the cost premium for renewables-only mixes relative to ones with full portfolios of low-, zero-, and negative-carbon technologies depending on assumptions about technologies, markets, and policies (Zappa et al. 2019; Bistline and Young 2019; Shaner et al. 2018; Sepulveda et al. 2018; Frew et al. 2016; Hirth 2015).

6.6.2.3 Widespread Electrification of End Uses

[Placeholder--This is placeholder text that will be revised in the next version of the chapter.]

Robust Conclusions. Most studies focusing on deep-decarbonization of the energy sector conclude that a cost-effective path includes substantial electrification of end-use services. A broad set of possible end uses are considered viable for electrification, particularly toward mid-century and beyond when the energy system might become carbon neutral .

Passenger and freight vehicle electrification will be a key component of carbon neutral energy systems. The rapid decrease in costs of batteries will enable continued decreases in the costs of electric vehicle. Electrification of transport will require not only electric vehicle but also large investments in a charging infrastructure. In buildings, space heating through heat pumps and cooking using electricity are also technically available. Mechanical drives are also an important area for electrification, replacing steam-driven options.

Flexibilities and Uncertainties. The key questions regarding end use electrification involve those applications in which electricity may not be advantaged relative to other carbon-free fuels such as hydrogen or biofuels. Applications that will be harder to electrify such as major components of the transportation system (air transport and marine transport) as well as high-temperature heat in industrial applications. While long distance trucking has also traditionally been considered hard to electrify, improvements in storage devices and decline in storage costs, as well as investments in charging infrastructure, could possibly lead to heavy duty trucking electrification. In some regions across the globe, transportation of freight via electric rail will likely be part of the effective strategies for freight decarbonization.

6.6.2.4 Alternative Fuels in Hard-to-Decarbonize Sectors

Robust Conclusions. Climate-neutral hydrocarbons (e.g., methane, petroleum, methanol), hydrogen, ammonia, or alcohols can be produced without fossil fuel inputs. For example, liquid hydrocarbons can be synthesized 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). Such energy-dense fuels may be critical sectors that are difficult to electrify), such as long-haul aviation (NAS), 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.

Flexibilities and Uncertainties. The literature focused on difficult-to-decarbonize sectors is quite limited, providing little guidance on the most promising or attractive technological options and systems for avoiding these sectors' greenhouse gas 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. 2018).

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. 2018). These biofuels could conceivably be targeted to difficult-to-decarbonize sectors, but face substantial challenges related to their life-cycle carbon emissions, cost, and further scalability (Tilman et al. 2009; Staples et al. 2018). The extent to which biomass will supply liquid fuels in a future climate-neutral energy system will thus depend on advances in conversion technology that enable use of 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 climate-neutral fuels, and integration of biomass production with other objectives (Lynd 2017; Laurens 2017; Williams and Laurens 2010).

Costs are the main barrier to synthetic hydrocarbons. Hydrogen is a constituent of such hydrocarbons (as well as in ammonia and alcohols). Today, most hydrogen is supplied by steam reformation of fossil methane (CH_4 into CO_2 and H_2) at a cost of $1.30-1.50 per kg (Izquierdo et al. 2012). Non-fossil hydrogen may instead be obtained by electrolysis of water, but the cheapest and most mature electrolysis technology today uses alkaline electrolytes together with metal catalysts to produce hydrogen at a cost of roughly $5.50/kg H_2 (assuming electricity costs of U.S. $0.07/kWh and 75% utilization rates) (Graves et al. 2011). At this cost of hydrogen, the minimum price of synthesized hydrocarbons would be $1.70/liter of diesel equivalent (or $6.50/gallon and $50 per GJ, assuming carbon feedstock costs of $100 per ton of CO_2 and very low process costs of $0.05/liter or $1.50 per GJ) (Graves et al. 2011). Research and development efforts are targeting 60-80% reductions in future electrolyzer costs, which may use 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. 2017a; DOE 2018; Saba et al. 2018; Kuckshinrichs et al. 2017).

The carbon contained in climate-neutral hydrocarbons must also have been removed from the atmosphere either through direct air capture 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 direct air capture technologies, targeting costs of roughly $100 per ton of CO_2 (Darton and Yang 2018; Keith et al. 2018).

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 climate-neutral fuel production at scale (McKone et al. 2014).

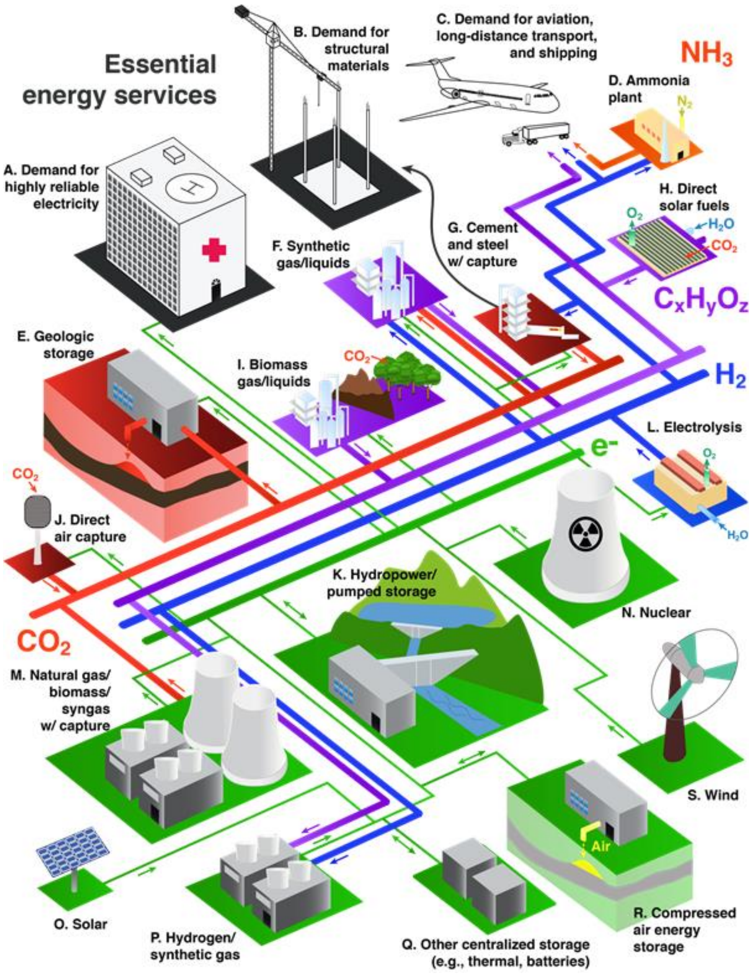


Figure 6.32 Energy System from Davis et al. as an example of methods to address hard-to-electrify sectors. (Source: (Davis et al. 2018)

Box 6.17 The hydrogen economy

The "hydrogen economy" has often been raised as an important potential option for a carbon-neutral economy. In reality, the hydrogen economy refers only to a portion of a low-carbon or carbon-neutral economy. The hydrogen economy focuses on the extensive use of hydrogen as a low carbon fuel, particularly for heating, hydrogen vehicles, seasonal energy storage, long distance transport of energy and fuel for electricity generation. Hydrogen fuel-cell based vehicles could supply heavy-duty vehicles (e.g. buses, trains and lorries) and potentially lighter vehicles for longer-range journeys. Hydrogen could also replace natural gas-based electricity generation, enabling reduction in emissions in electricity system. In order to transport hydrogen, for distances within a county or region, the existing gas infrastructure could be used. For longer distances (e.g., through continents), hydrogen (mainly through ammonia) can be transported as liquid natural gas, which is a well-known industry world-wide. This provides important opportunity for a world-wide low-carbon hydrogen economy.

Many publications discuss the potential role of hydrogen in providing energy to transport, heat and electricity generation (e.g. WEC and IEA). Recent developments and improvements in hydrogen production technologies provide evidence related to the increasing role of hydrogen as a core future energy fuel. This is indicated through efficiency increase and capital cost reduction of the existing technologies (e.g. SMR) as well as development of emerging advance technologies (e.g. electrolysers) for hydrogen production. In terms of use of hydrogen for power generation, it has been announced that gas turbines should be able to operate completely on hydrogen by 2030, which would provide emission-free power generation.

There are a number of benefits to a hydrogen economy. Hydrogen could be attractive in the future for countries as a way to diversify their economies by exporting low-carbon energy as hydrogen or hydrogen-based fuels, or importing hydrogen to benefit from strong competition that would restrain costs. When hydrogen is deployed alongside electricity infrastructure, electricity can be converted to hydrogen and back again, or further converted to other fuels, making end users less dependent on specific energy resources and increasing the resilience of energy supplies. In a carbon-neutral energy system, such hydrogen trade would effectively enable trade and storage of wind and solar renewable sources between different regions to overcome seasonal differences. Furthermore, hydrogen could provide a strong resource for storing reserves of energy strategically in a highly electrified low carbon world.

The concerns and weaknesses regarding the hydrogen economy are mainly related to the production and use of hydrogen. Hydrogen production from fossil fuels (i.e., SMR/ATR with CCUS for natural gas, and gasification of biomass and coal) is not an option in a carbon-neutral energy system, since carbon emissions will remain. Hydrogen must therefore be produced by other means. Producing hydrogen through electrolysers is still expensive. In the context of the application of hydrogen appliances and carriers, there are concerns related to safety associated with flammability, toxicity, and storage.

6.6.2.5 More Efficient Use of Energy than Today

[Placeholder--This is placeholder text that will be revised in the next version of the chapter, including references.]

Robust Conclusions. Energy efficiency strategies are generally perceived as being flexible, cost-effective, with a potential for large scale deployment, and with potential to be deployed at scale. For this reason, the vast majority of the studies in the literature find that energy efficiency and conservation strategies will be important contributors to carbon-neutral energy systems.

Research has repeatedly highlighted the range of cost-effective, higher-efficiency energy technologies and the potential of these technologies. For example, in the building sector, areas for increased efficiency can be found in lighting, heating and cooling, cookstoves, insulation, passive and active solar design for heating and cooling, alternative refrigeration fluids, and recovery and recycling of fluorinated gases, among others (see Chapter 9). Similar alternatives exist in the industrial and transportation sectors (see Chapters 10 and 11)

Flexibilities. While the potential for increased efficiency is vast, there is substantial flexibility and uncertainty regarding how much of this potential will actually be tapped. Greater efficiency will reduce low-carbon energy requirements and vice versa. While energy efficiency strategies may be cost-effective and sometimes even reduce overall lifecycle costs, consumers and businesses often do not take advantage of these opportunities. The energy efficiency gap – the difference between what would seem to be economically appropriate and what actually occurs in reality – has variously been attributed ways that the goals of consumers might deviate from economic efficiency and a range of market failures including environmental externalities, split incentives, lack of access to financing, and limited information, among others. Regardless, the difference between what would appear, on the surface, to make and what happens in reality implies a great deal of uncertainty about the ultimate configuration of the level of efficiency in carbon neutral energy systems.

An additional challenge in defining the degree of efficiency in carbon-neutral energy systems is that efficiency itself is difficult to define and describe across full economies. Measures such as energy per capita or per GDP reflect not only efficiency but also factors such as levels of development, industrial structure, landscape, consumption overall (e.g., size of houses), and urban forms. In addition, energy efficiency represents such a large set of technologies that aggregate measures can be difficult to define.

[Placeholder--more information on measuring energy efficiency from a paper currently under review will be included in the next version of this section.]

6.6.2.6 Greater Reliance on Integrated Energy System Approaches

Robust Conclusions. Carbon neutral energy systems are expected to be more interconnected than those of today. 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. 2018). Systems integration and sectoral coupling are increasingly relevant to ensure that climate-neutral energy systems are reliable, resilient, and affordable (EPRI 2017). Coordinated investment and operations across currently discrete energy industries and industrial processes could be important to lower system costs, increase reliability, and ensure that lumpy costs of R&D and infrastructure account not just for current needs but also for those of future net-zero energy systems.

The characteristics of supply- and demand-side options across sectors should be adequately reflected in planning and operations for this integrated system of systems. New market design considerations, attributes (e.g., resiliency, flexibility, sustainability), and business models are important to send appropriate price signals to coordinate investments and operations. Compensation would have to be available for resources to have an incentive to provide desired attributes and behaviors in net-zero energy systems when and where they are needed, which could include cost reductions, the provision of reliability services, flexibility to mitigate impacts of system variability and uncertainty, resiliency, and locational value (EPRI 2018). Increasing spatial and temporal granularity in markets and pricing are likely to become more common throughout the energy system, a trend that has already started in power markets to accommodate more variability from supply-side resources (Ela et al. 2017, 2014).

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 (and increasing the utilization rates of capital-intensive assets), enhancing the geographical diversity of resource bases, and smoothing demand. The feasibility of carbon-neutral 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, climate-neutral liquid 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. 2018).

Flexibilities and Uncertainties. There are few detailed archetypes of integrated energy systems that provide services with zero-gross 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 (Davis et al. 2018; Jenkins et al. 2018b; van Vuuren et al. 2018; Shih et al. 2018; Moore 2017; Smith et al. 2016b).

In light of these uncertainties, there are modeling and analysis needs for systems integration research, which, require greater integration across disciplines. The coupling of systems will be informed by linked analytical frameworks (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 will 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. The greater supply- and demand-side integration creates a need to understand behaviors of decision-makers in different sectors and to quantify heterogeneity for firms and households, which are challenges given low-levels of experience with emerging technologies, nascent markets, and variation in household preferences and socioeconomic characteristics (McCollum et al. 2018a).

Challenges associated with integrating carbon-neutral 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. Deep decarbonization offers new opportunities and challenges for integrating different sectors. 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 2019a), in some cases aiding renewables integration and others adding complexity. 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).

6.6.2.7 Use of Carbon Dioxide Removal

[Placeholder--This subsection is under development. The major points are included, but only limited text is currently in place to express these points.]

Robust Conclusions. A major challenge for reaching carbon-neutrality in energy systems is addressing hard to decarbonize sectors such as aviation and some industrial applications. Many analyses (Davis, 2018) and many integrated assessment modeling scenarios rely on CDR to offset emissions from hard-to-decarbonize sectors. This CDR can be associated with the energy systems either in energy production (e.g., BECCS) or as an energy user (e.g., direct air capture), and will make sense only in countries with sufficient capacity to store carbon.

Flexibilities. There are a number of different flexibilities regarding the contribution of CDR to carbon-neutral energy systems. One flexibility is the overall quantity of CDR. The need for CDR depends largely on the degree of success in addressing hard-to-decarbonize sectors. The greater the degree of success in decarbonizing these sectors, the lower will be the requirement for CDR for this purpose, and vice versa.

CDR can also be included in energy systems either on the supply or demand side. Much has been made of the role of BECCS as a CDR option (IPCC 2018b, 2013). Whether associated with electricity, liquid fuels, or hydrogen production, BECCS would be associated with energy supply and conversation. The proportion of these three different options will depend, among other things, on the degree of use of these the three different energy carriers – electricity, biofuels, and hydrogen – in the carbon-neutral energy system. CDR may also be deployed through energy using technologies such as direct air capture.

Finally, some countries are not endowed with meaningful CO_2 storage capabilities, limiting their ability to deploy CDR. While these countries may ultimately purchase CDR in other countries if reaching carbon-neutrality is too difficult in their own. Under the definition in this section, these would not be considered carbon-neutral energy systems at a national level.

6.6.3 The Institutional and Societal Characteristics of Carbon-Neutrality

The transition to a carbon-neutral energy system is not just a technological one; it is also one that requires shifts in institutions, organizations, and society more generally. As such, it involves changes in the markets institutions that govern society, alongside the often-discussed changes in supply, technology, or (Andrews-Speed 2016). There are at least three ways in which institutions are instrumental for low-carbon transition and for affecting consumption patterns and household behavior (Figure 6.).

One level of institutional interactions reflects the embedded institutions, norms, beliefs and ideas that would need to be different than today to support carbon neutrality. One change relates 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) Another refers to the institutional environment, the political or legal systems that govern exchanges or protect property rights. Here challenges might relate to regulations or subsidies that continue to favor incumbent or carbon-intensive systems over the technologies that will be necessary to underpin a carbon-neutral energy system (Sovacool 2017). More generally, carbon-neutral energy systems will need to new regulatory frameworks to, for example, manage a more interconnected grid or manage underground storage of CO_2. A third and final level of institutions govern specific transactions, such as firms or networks that supply energy fuels or services. Current business actors such as these are typically resistant to disruptions, even if such disruptions may be beneficial from a broader societal perspective (Kungl 2015). Recent research suggests that such institutional barriers to decarbonisation at the transactional institution level exist in Germany (where research suggest DSOs are hostile to renewable electricity, e.g. (Schmid et al. 2017) or China (where some state planners seek to curtail renewable energy, e.g. (Mori 2018)).

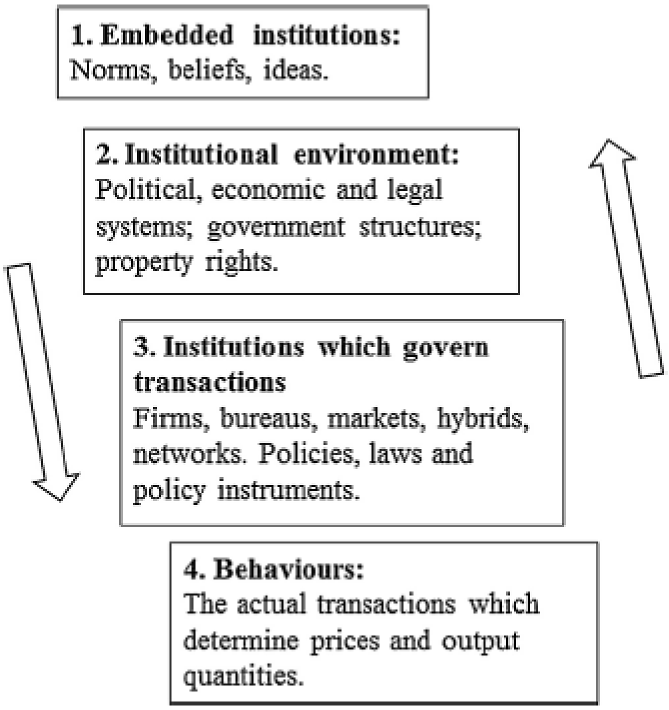


Figure 6.33 The three levels of institutions (1-3) which collectively govern actor behaviors (4). Source: Andrews-Speed 2016

To give an example, it has been asserted that the United States energy system has two broad institutional wings, one based upon lightly- regulated delivery of energy for transportation through liquid fuels, and the other based upon closely- regulated delivery of even larger amounts of energy in the form 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 recognized both local and national concerns through both state and federal regulatory agencies. These different types of institutional change in the United States—technical, financial, economic, and regulatory—are only at the level of a country, and relate to two energy systems. At the international level, such institutional challenges could become even more stark and complex (Van de Graaf 2013).

In addition to institutional change, societies acceptance of and interaction with carbon-neutral energy systems will need to be different than it is today (Figure 6.). [Placeholder for SOD]

6.6.4 Regional Circumstances and Carbon-Neutral Energy Systems

[Placeholder for SOD--This section is a rough sketch of the intended section. It contains text that articulates the basic themes we intend to pursue, but without the literature support that is needed and that might alter the conclusions.]

While the literature has identified several robust characteristics of carbon-neutral energy systems, there remains a great deal of flexibility in which system or systems any country might pursue. Countries may emphasize energy supply over demand reduction; deploy different resources; engage at different levels in international energy trade; support different energy industries with different needs; 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? Without some sense of where they might be headed in the long-run, it is difficult to make directed decisions and investments today.

A short assessment like this report cannot give definitive answers to this question. The answer depends to much on local circumstances and priorities, such as local resource bases and societal postures on key societal priorities such as energy access, energy security and regional energy integration, economic competitiveness and industrial policy. Moreover, it is not possible to predict how technology options and society will evolve over the coming decades, so any plans will necessarily only be starting points and will evolve over time in response to the evolving societal and technological environment.

Energy system and integrated assessment models are used extensively to support planning in this regard. While important inputs, it is also important to acknowledge the weaknesses of these tools for real-world planning. These models are frequently used in an “economic optimization” framework, which means that they look for the single best future system based on simple economic cost metrics, which are only one of many relevant important characteristics of future systems. Furthermore, while optimization identify the single best system based on some set of criteria, there are often many different systems that have very similar outcomes. In response to this, studies are increasingly deploying scenarios exploration methods in which multiple scenarios or futures are evaluated across multiple objectives. But even in these cases, the set of characteristics that these models can evaluate is often limited and not critical to local decision making. Furthermore, not all countries, let along businesses, cities, and states have the capacity to engage in extensive modeling studies.

There is an increasingly robust literature that supports a deeper understanding of the factors that might influence which energy systems might or might not be most appropriate for any country or other actor. Here we discuss several of these factors.

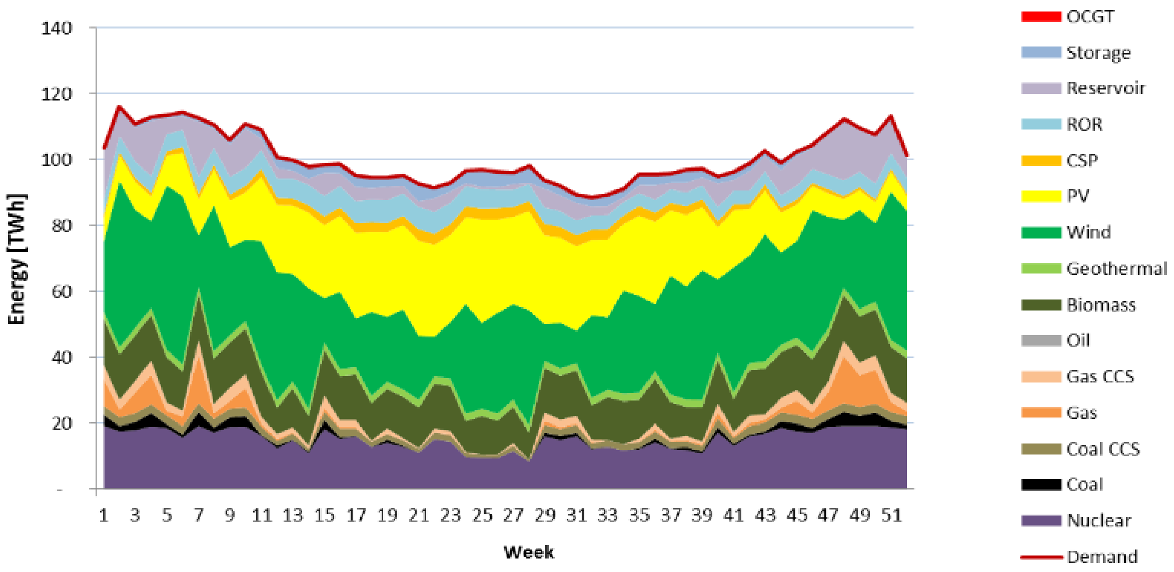
Resource Base. Among the most important criteria is a countries energy supply resources base (see Section 6.4). A natural conclusion is that countries might plan for futures that best take advantage of their indigenous resources. This relationship is subject to several caveats, however. Countries with resource bases that are easily tradeable, for example, fossil fuels, may choose to trade those resources rather than using them domestically if this has economic returns. Still other countries may double down on these resources if they are connected to international markets. For example, regional electricity generation could allow countries endowed with expansive renewable electricity generation resources to produce well beyond their own domestic needs if they can find other countries intent on purchasing these resources. This linkage to resources has natural implication for technology emphasis.

Regional Integration. Countries vary substantially in their energy linkages to other countries. For example, a number of countries may all participate in a common electricity grid. Countries may also trade in a wide variety of additional carriers, from hydrogen to various forms of bioenergy. In all of these cases, regional integration provides substantial flexibility to consume energy that they have not produced or to produce energy that they will not consume. For example, countries may be able to use a greater proportion of their intermittent renewable generation if they are connected to other countries with the capability to ingest this power. This could potentially allow countries to adjust their portfolio of electricity technologies to better match the overall structure and needs of the grid. Similarly, countries with substantial CO_2 reservoir capacity could purchase biofuels from countries with substantial capacity to produce biomass.

Box 6.18 Regional integration

Given the significant geographical variations in the capacity factors of renewable generation resources across different regions and continents, a regional (global) approach compared to a local approach to deployment of renewables could facilitate a more cost-effective energy system decarbonisation. There may be significant benefits in strengthening regional electricity transmission infrastructure to enable cost effective deployment of renewable generation.

Future weakly production patterns of renewable generation are shown in figure below, demonstrating that solar production in southern Europe is dominant in summer while wind generation in northern Europe is more significant in winter, which would make regional/continental approach of decarbonisation cost effective.



Box 6.18, Figure 1 Projection of weakly production patterns of low carbon generation in Europe (starting in January)

As an example, a fully coordinated deployment of renewable sources in Europe by 2030, would save 160 GW of renewable energy source capacity being built while producing the same amount of renewable energy. This could save more than €150bn of capital expenditure by 2030, since the transmission reinforcement costs are much lower than the savings in investment in renewable generation (~10%). Although the cost of renewables falling, it will still be important to consider benefits of regional decarbonisation strategies. Furthermore, interconnection can significantly reduce the local energy balancing cost and investment in peaking plant needed to meet security of supply requirements.

Development of transmission infrastructure that would provide access to very strong solar resources in Sahara Desert could significantly reduce cost of energy system decarbonisation in Europe. As scenario analysis demonstrates, 15% of Europe's electricity demand could be supplied from solar farms (PV and CSP) located in Sahara Desert.

Furthermore, west-east interconnection can enhance utilisation of renewable generation and further reduce cost of decarbonisation. Due to the different time zones, e.g., electricity from solar generation produced in Middle East (with higher capacity factors) could be used in Europe even after sunset.

As hydrogen may have significant role in decarbonisation of the energy sector in future, the generated electricity by solar or wind can be used to generate hydrogen through electrolyses process, and then shipped to other locations. 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.

Linkages to other Societal Priorities. Climate mitigation is only one of many priorities for countries. These other priorities will have a critical role in defining future energy systems (Table 6.9). Key priorities include, among others, energy security, air pollution, energy access, and technological leadership.

Table 6.9 Implicatios of Societal priorities on Carbon-Neutral Energy Systems [Placeholder for SOD]

Societal Priority	Implications for Carbon-Neutral Energy Systems
Energy Security	To be completed
Energy Access	To be completed
Air Pollution	To be completed
Technological Leadership	To be completed

Societal Preferences. Governments and businesses respond to the preferences of the individuals that make up a country or that purchase products from businesses. Studies indicate that preferences for carbon-neutral systems differ across regions and groups, suggesting that region specific solutions would be needed and that preferences of different groups need to be balanced. It is important to understand which types of carbon-neutral energy systems are preferred by relevant actors, as strong public opposition can halt the transition to carbon-neutral energy systems. Little is known about public acceptability of full carbon-neutral energy systems, as most study focus on the acceptability of single options rather than combinations of options that would constitute a system change. At the same time, the existing research does provide insights into technologies might be utilized in carbon-neutral systems. For example, studies have variously shown that people in the U.S. seem to prefer diverse portfolios that include energy efficiency, nuclear, coal with carbon capture and sequestration, natural gas and wind (Mayer et al. 2014)(Fleishman et al. 2010; Bessette et al. 2014); people in the US are willing to pay more for electricity produced by renewables compared to the current energy mix, particularly when climate and health benefits of a renewable energy mix are emphasized (Sergi et al. 2018); people in the U.K. prefer renewable energy and personal actions over nuclear, fossil fuels and CCS (Demski et al. 2017)(see also (Jones et al. 2012); Germans prefer renewable portfolios over nuclear (Scheer et al. 2013); the public in the Netherlands is generally more favorable about energy efficiency, biomass, and wind compared to CCS and nuclear (De Best-Waldhober et al. 2009; Van Rijnsoever et al. 2015); the acceptability of energy efficiency and energy savings is high in Switzerland (Volken et al. 2018), renewables are preferred to natural gas and geothermal energy, and nuclear receives the least support (Bessette and Arvai 2018); Europeans prefer renewables, such as wind, solar and hydropower to nuclear

(Steg 2018); Canadians prefer portfolios with highest reductions in GHG emissions, despite their higher costs (Bessette and Arvai 2018); generally, 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). While acknowledging that preferences can change over time.

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

6.7.1 Transition Pathways to low carbon energy systems

CO_2 emissions from energy systems are the biggest single contributor to the anthropogenic GHG emissions and are expected to continue to grow without more stringent mitigation. This section illustrates the future evolution of the energy systems, exploring the primary energy sources, mitigation options, and end use characteristics of pathways leading to stabilization at different temperature levels. It also addresses the question of when energy-system emissions need to reach net zero to meet different temperature goals.

6.6.4.1 CO_2 emissions from fuel combustion (global and regional)

A large body of global mitigation pathways have been produced using integrated assessment models (IAMs). IAM scenarios are valuable for assessing the role of the global energy system in mitigation because they are based on internally consistent assumptions about socio-economy, energy system, land use, technological change, and their complex interactions (Krey et al. 2019). The Shared Socioeconomic Pathways (SSPs) were developed in response to the large uncertainties in future socioeconomic changes. They provide plausible descriptions of how the future might unfold in several key areas, including GDP and population growth (Riahi et al. 2017a). The SSPs vary widely in their underlying socioeconomic assumptions, energy supply structure, technological change and consumption patterns (Bauer et al. 2017). The baseline scenarios of SSPs – those assuming no increase in climate action – provide a window in to how emissions might vary without any further climate mitigation. Global CO_2 emissions from fuel combustion increase in most baseline scenarios but span a broad range, reflecting the underlying differences in the development of future energy systems (Bauer et al. 2017; Riahi et al. 2017b) (Figure 6.). The highest baseline emissions from the energy sector (SSP5) reach approximately 120 $GtCO_2$/yr in 2100, which is about four times large than the current emissions. Emissions reach about 30 $GtCO_2$/yr in 2100 in the lowest SSP (SSP1). Patterns of the future CO_2 emissions development also vary widely across regions.

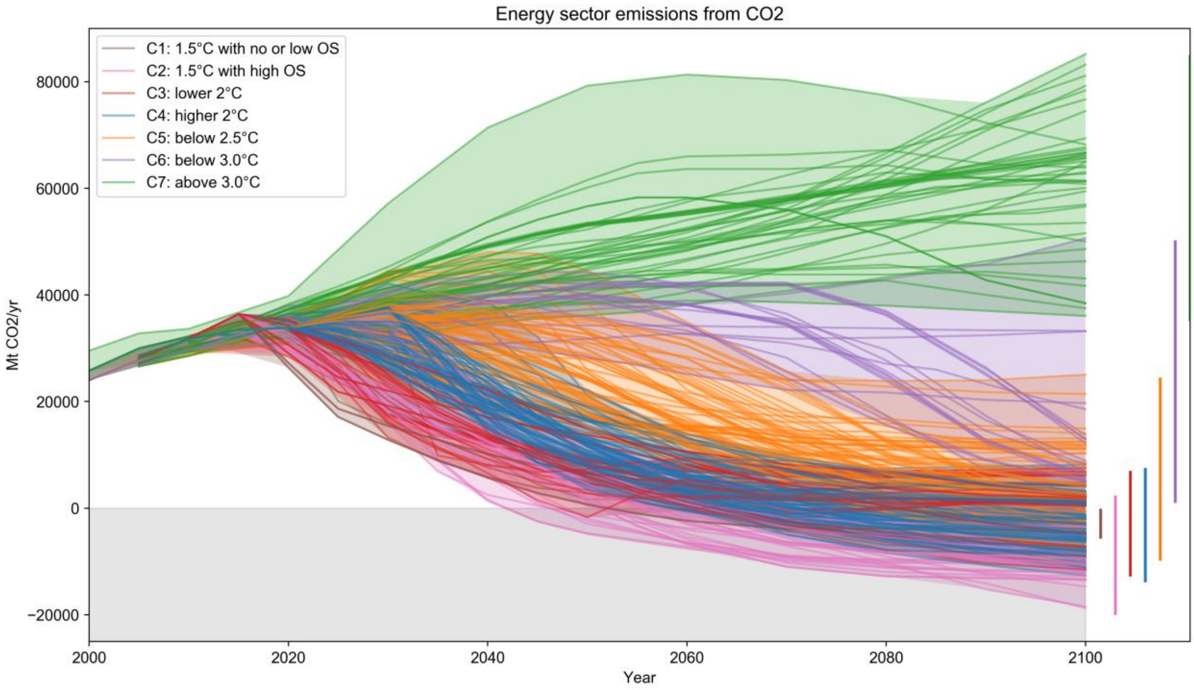


Figure 6.34 Global energy sector CO_2 emissions associated with different temperature goals (IPCC Scenario Database)

IAM stabilization scenarios provide insights about the nature of energy system evolution associated limiting temperature change. For stabilization scenarios, the range of emission pathways narrows substantially, but there are significant differences in the energy systems across the underlying socioeconomic backdrops represented by the SSPs. Smaller energy demand in SSP1 allows for a relatively smooth transition to low carbon energy systems. On the other hand, high reliance on fossil fuels in SSP5 leads to a high and late emissions peak. This poses mitigation challenges and requires a substantial net negative emissions technologies in the later part of the century (Bauer et al. 2017). Regardless of these socioeconomic backgrounds, both the 1.5°C and 2°C scenarios are largely similar in that both require rapid CO_2 emission reductions until mid-century, but the transformation is more prominent and rapid for the1.5°C scenario (Rogelj et al. 2018a). 1.5 °C scenarios require a higher pace of annual average CO_2 emissions reductions at around 3.0% per year over the period 2020–2040, compared to 1.6% per year for 2°C scenarios (Gambhir et al. 2019; Rogelj et al. 2018a). IEA's Sustainable Development Scenario, which likely limits the temperature rise to below 1.8 °C, sees CO_2 emissions from energy systems peak at around 33 Gt (equivalent to 2018 emissions), and then fall at 3.8% per year to net zero emissions by 2070 (IEA 2019f).

6.6.4.2 The timing of carbon-neutral energy systems

Achieving net zero CO_2 emissions is requisite for stabilizing climate. Thus far nearly 70 countries or regions have announced long-term net-zero emissions targets (IEA 2019f). An important issue in this regard is the timing of net-zero emissions associated with different long-term temperature goals.

In most scenarios power sector CO_2 emissions reach net zero before economy-wide CO_2 emissions reach net zero. This reflects higher accessibility to zero or negative emission technologies (Rogelj et al. 2018a, 2015b; Clarke et al. 2014) in the power sector. Overall GHG emissions reach zero after net CO_2 emissions reach zero because non-CO_2 emissions are difficult to reduce. The timing of net-zero emissions varies across countries depending on the structure of energy systems and domestic circumstances (IEA 2019f).

The availability of net zero or negative emissions technologies and the stringency of climate policy determine the timing of net zero emissions. The year of net zero CO_2 emission moves earlier as the climate target becomes stringent. With an increase in electrification of energy end use, emissions from electricity are almost zero around 2050 in both 1.5 °C and 2 °C scenarios. For 2°C pathways, economy-wide CO_2 emissions become net zero between 2060 and 2075 and GHG emissions reach net zero around 2090 (Rogelj et al. 2015b). The timing of net zero CO_2 emissions for 1.5°C scenario is about 10–20 years earlier than likely 2 °C scenarios. For scenarios limiting temperature change to 1.5°C, global CO_2 emissions become net zero earlier at around 2045–2060, and net zero GHG emissions are reached around 2055–2075 (Rogelj et al. 2015a).

The level and timing of peak CO_2 emissions impact the timing of net zero emissions given the constraint of a long-term temperature goal. In the 2 °C scenarios, it is estimated that two decades delay in the peak in global CO_2 emissions lead to about 15 years earlier net zero CO_2 emissions. The year of reaching net zero GHG emissions has inverse relationship with near-midterm emission level. 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, 2019).

Climate metrics, such as the global warming potential (GWP) and the global temperature change potential (GTP), their time horizons and their values, matter in assessing the timing of net-zero emissions. GWP weighted emissions over a 100 year period (GWP-100) are usually used within the UNFCCC, but other options are potentially available (Fuglestvedt et al. 2018; Collins et al. 2013). If 100 year time horizon is applied, the timing of net zero emission is in the latter half of the century. The timing of reaching net-zero emissions for the 1.5°C and 2°C scenarios move beyond 2100 if 20 year time horizon for GWP or GTP is used (Rogelj et al. 2015b; Fuglestvedt et al. 2018).

The discount rate also matters in the assessment of the timing of net zero emissions (Mercure et al. 2018; Bednar et al. 2019). The choice of the discount rate in IAMs affects the shape of emission pathways through the change of the cost profile, which create a difference in the timing of reaching net zero emission accordingly. Higher discount rates defer climate investments. Given a particular end of century temperature goal, large-scale CDR may be deployed in the latter half of the century as a consequence of an overshoot in cumulative emissions (Obersteiner et al. 2018). Lower discount rates leads 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. The year of net negative emissions under a 1000 $GtCO_2$ carbon budget pushes back from 2072 to 2079 if the discount rates move from 5% to 2% (Emmerling et al. 2019).

6.6.4.3 *Energy transition strategies*

Limiting temperature change requires a fundamental transformation of the global energy system, and there is no single technological route to achieve the targets (Clarke et al. 2014; Rogelj et al. 2018a). Supply-side low-carbon technology options include a rapid shift away from fossil-fuel toward large-scale low carbon energy supplies, such as renewables and nuclear power, and deployment of carbon-dioxide removal (CDR) technologies. As an energy carrier, electricity plays a key role in decarbonizing energy systems. The portfolio of demand-side mitigation options includes improvement of energy efficiency, an increase in electrification of energy end use, replacing fossil fuels by electricity, decarbonization of fuels to bio-energy, development of efficient urban infrastructure, and lifestyle and behavioral changes (Clarke et al. 2014; van Vuuren et al. 2018; Grubler et al. 2018; Rogelj et al. 2015b; Luderer et al. 2018).

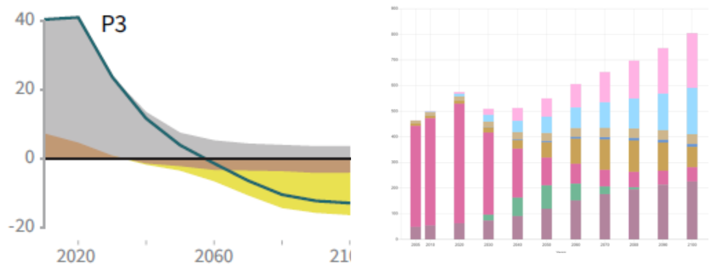
6.6.4.3.1 Supply side

Currently, energy supply accounts for about 45% of global energy-related CO_2 emissions (Luderer et al. 2018) and the share of low-carbon technologies in energy supply is below 20%. They need to reach around 60% (40–70%) of the energy by 2050 for 2°C target, and even more for 1.5°C target (Riahi et al. 2017a; Rogelj et al. 2015a). Key technologies contributing to emissions reduction, however, depends heavily on scenarios. Some scenarios emphasize the role of renewables, others depends on fossil fuels plus CCS or nuclear, and some others have mixed technology portfolio (Riahi et al. 2017a; Bauer et al. 2017)

Box 6.19 Illustrative energy system transitions

This section highlights illustrative energy system archetypes that help to clarify the variation in assessed ranges for net zero emission energy systems. These are selected in particular to illustrate the variety of underlying characteristics across net zero emission energy technology options, ranging from very low energy demand regime, renewable energy dependent regime, fossil fuels plus CCS and BECCS dependent regimes, and mixed portfolio of low carbon technologies regime.

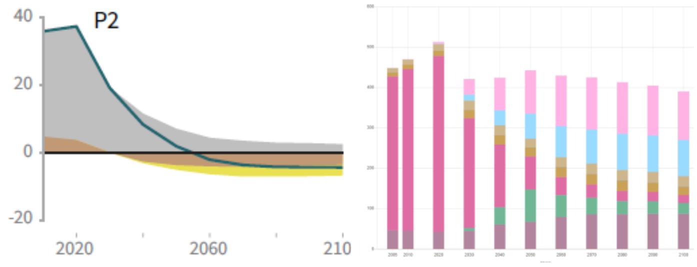
Transition by Mixed Technology Portfolio (Middle of the road)



Societal as well as technological development follows historical patterns. Emissions reductions are achieved by mixed technology, including renewables, nuclear and fossil fuels with CCS

Box 6.19, Figure 1

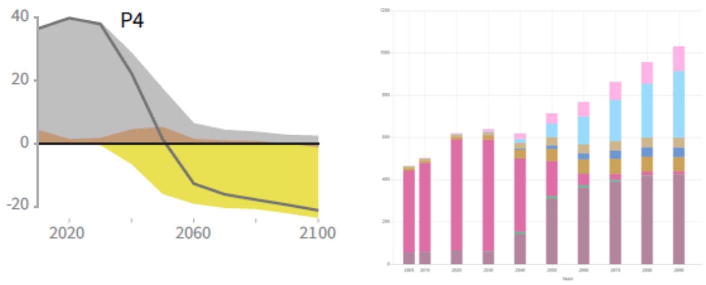
Renewables Driven Transition (Sustainability)



Variable renewable energy (VRE), such as wind and solar, contributes a lot to the low-carbon transformation of the power sector. VRE's variability and uncertainty pose new challenges for power systems. Battery energy storage systems that provide flexibility services to the grid.

Box 6.19, Figure 2

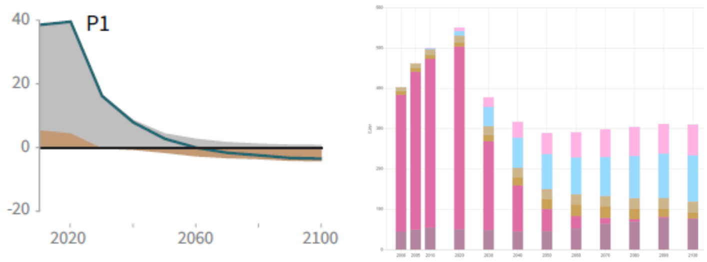
CCS Driven Transition (Fossil-fuelled development)



The relatively high fossil energy use in the first half of the century and large-scale deployment of BECCS in the latter half of the century. Required huge land areas for bio crops production have sustainability concern.

Box 6.19, Figure 3

End-user Driven Transition (LED)



Technological innovation, novel energy services and people’s behavioural changes bring about rapid social and institutional changes and reduce energy demand. Low energy demand enables low carbon supply-side transformation smoothly.

Box 6.19, Figure 4

Reference: IAMC 1.5°C Scenario Explorer hosted by IIASA

The long-term transition toward climate stabilization involves a significant reduction in fossil fuel consumption, especially the consumption of coal (Rogelj et al. 2018b; McCollum et al. 2014; Bauer et al. 2018, 2016a). From near to midterm, however, the fossil fuels still continue to contribute to energy supply. Today about 80% of primary energy is supplied by fossil fuels, and this share moderately drops down to 78% in 2030 for 2°C scenarios and 67% for 1.5 °C scenarios respectively (Gambhir et al. 2019). A decline in coal use is a consistent result across the scenarios literature (IEA 2019f; Riahi et al. 2017a; Krey et al. 2014b; Bauer et al. 2016b). The role of oil and gas is more mixed across the literature due uncertain factors such as the cost and deployment of non-fossil technologies and the utilization Carbon Capture and Storage (CCS) (McCollum et al. 2014). In one study, natural gas and oil account for 18% and 20% of primary energy demand by 2050 (IEA 2019f). Alternatively, non-fossil low-carbon energy sources, including renewables and nuclear power, grow in the long run. Particularly bioenergy scales up by 1–5% per year toward 2050 because it is a versatile substitute for fossil fuels. Demand for bioenergy increases to around 300 EJ per year at a maximum, mostly below 150 EJ per year in 1.5 °C scenarios (Rogelj et al. 2018a). Bioenergy serves as an important mitigation option for the decarbonization of fuels in transport, buildings and industry sectors (Luderer et al. 2014).

A number of studies highlight the importance of power sector in reducing CO_2 emissions from the energy system as a whole because electricity can be generated in a carbon free manner with diverse technology options, including renewables, nucelar, fossil fuels with CCS (Clarke et al. 2014; Krey et al. 2014b; Williams et al. 2012). This allows a higher degree of technology flexibility in reducing CO_2 emission than in other sectors of the energy system. Accelerated electrification with a combination of full-scale decarbonization in power supply is one of the core strategies to decarbonize energy system (Waisman et al. 2019; IEA 2019f; Sugiyama 2012; Zou et al. 2015; Rockström et al. 2017; Luderer et al. 2018, 2017).

6.6.4.3.2 Electricity

Scenarios consistently suggest that the electrification rates increase over time and that the pace of electrification appears faster as climate targets become stringent (Riahi et al. 2017a; Bauer et al. 2017; Clarke et al. 2014; Sugiyama 2012; Krey et al. 2014b). Aggressive electrification of energy end uses, such as widespread of electric vehicles (EVs), and electric heat pumps for water heating and air conditioning, is needed to achieve Paris target. Today about 20% of final energy demand is electricity, and the share expands to 43% by 2050 in the 1.5 °C scenarios and less than 35% in the 2 °C scenrios (Gambhir et al. 2019). In low energy demand scenario electrification is further accelerated to the share of electricity to 46% in 2050 (van Vuuren et al. 2018).

In 2018, global electricity generation reached 26,600 TWh and emissions from power generation were about 13 Gt, or 38% of total CO_2 emissions from energy systems (IEA 2019f). Electricity demand increases roughly double by 2050, and quadruple to quintuple by 2100 (Bauer et al. 2017; Luderer et al. 2017; IEA 2019f). Even though electricity demand increases, CO_2 emissions from the power sector fall down as carbon intensity of electricity decreases in the climate mitigation scenarios. Reflecting the contribution of low carbon technologies, including renewables, nuclear and CCS, the carbon intensity of electricity supply goes down from 475 g CO_2/kWh in 2018 to around zero CO_2/kWh by 2050 in both of the 1.5 °C and 2 °C scenrios (IEA 2019f; Rogelj et al. 2018b, 2015a).

[Placeholder for SOD-Figure 6.35 [*To be included*] Electrification rate (x-axis: the ratio of electricity to final energy demand) and the share of low carbon power supply option (y-axis: the share of renewables, nuclear, and fossil fuels with CCS to total electricity production) for the baseline, 2°C and 1.5°C.]

Variable renewable energy (VRE), such as wind and solar, contributes a lot to the low-carbon transformation of the power sector in the mitigation scenarios. In particular combined wind and solar account for more than half of the electricity supply in 2°C scenarios in the long-term (Fuss et al. 2018; Luderer et al. 2017). VRE has a couple of defining features that are different from the conventional sources of electricity; (a) Their resource potential does not deplete over time and their quantity and quality differ vastly at the regional level; (b) Wind and solar have no fuel costs with relatively small operations and maintenance costs in generation, so their competitiveness measured in the levelized cost of electricity (LCOE) is predominantly the result of capital costs, which undergo substantial reduction and are expected decline further; and (c) they are not possible to produce electricity simultaneously with demand, so flexibility of the power system, from generation to transmission and distribution systems, storage, and demand-side management, is required for balancing fluctuation (IRENA 2019e; IEA 2014; Luderer et al. 2017). Battery energy storage systems that provide flexibility services to the grid are promising options to integrate higher shares of VRE. Currently renewables, including solar PV, hydropower, wind and geothermal, supply almost 25 % of global electricity output (IEA 2019g). In low stabilization scenarios wind and solar PV scale up substantially, but their extent of contribution range widely depending on the scenarios. IEA's Sustainable Development Scenario shows the share of renewables in generation increases to 66% by 2040 (IEA 2019f). Another literature suggest that 60–80% in SSP1 and 32–79% in SSP2 of electricity is supplied by non-biomass renewables in 2050 for the 1.5°C scenarios (Rogelj et al. 2018b).

6.6.4.3.3 Demand side

Future energy demand spans widely in the SSP baseline scenarios. At the upper end of the range, global final energy demand is projected to be around 1200 EJ per year in 2100. At the lower limit global energy demand increases slowly toward mid-century and stable at around 550 EJ per year in the latter half of the century (Riahi et al. 2017a; Bauer et al. 2017). Accordingly, mitigation efforts for achieving stringent climate targets differ across the SSPs because the challenges of mitigating climate change depend on socioeconomic conditions and the size of energy demand. In a SSP3 world under heterogeneous regional development with a low international priority for addressing environmental concerns, any integrate assessment models could not find a solution to limit warming to below 2°C (Riahi et al. 2017a; Rogelj et al. 2018b). Higher energy demand implies the significance of the future challenges to mitigation due to limited low-energy supply options, whereas the lower energy demand increases the feasibility of low-carbon energy supply systems. An average annual energy demand between 2010 and 2100 for the majority of the 1.5 °C scenarios is below 400 EJ per year, which indicates energy demand gradually increases from the current level of 350 EJ per year to about 450 EJ per year by 2100 (Rogelj et al. 2015a).

Energy efficiency improvements not only play a key role in any low stabilization scenario (Rogelj et al. 2015a), but also contributes to sustainable development by reducing energy use and CO_2 emissions without undermining the welfare of society (Waisman et al. 2019). Energy end-use has large potential to improve efficiency and makes dominant contribution to mitigating climate change (IEA 2019f; Sugiyama et al. 2014; Wada et al. 2012).

Technological innovation and novel energy services may bring about rapid social and institutional changes, delivering economic growth with lower energy demand. Urbanization, novel energy services, behavioural changes of end-users, and information innovations could allow us to consume less energy with higher living standards. Low Energy Demand (LED) scenario is different from the large body of scenarios in that the speed of social and institutional changes, reliance on stringent climate policy, emphasis on energy end-use and focus on structural changes in the intermediate and upstream sectors (Grubler et al. 2018). With this demand side transformation energy consumption drops to 245 EJ by 2050, around 40% lower than current size of energy demand (Grubler et al. 2018). Lifestyle and behavioural change, such as modal shift towards more mass transit, car sharing, moderate heating and cooling levels at homes and dietary change to low-meat healthy food, potentially reduce energy demand as well (van Vuuren et al. 2018). Such a low energy demand for end-use services enables low carbon supply-side transformation smoothly.

From sectoral perspectives, available low carbon options are much more limited and costly especially in the transport and industry mainly because electrification potentials are lean. Emissions from these sectors need to be reduced by fuel switching to biofuels, increasing technical efficiency, and reducing energy service demand.

In the buildings sector, electrification and improvement of energy efficiency are the primary means for decarbonization (IEA 2019f). Renovating thermal insulation of existing buildings to reduce heat loss through the building envelope has a significant energy-saving potential as well. Most of the energy-efficient appliances and building insulation involve higher upfront costs, which are usually recoverable by the saved energy costs over the lifetime of technologies. Consumers, however, often outweighs short term profitability and make myopic investment behaviour in the real world. Human-related factors and behavioural issues need to be addressed in the energy transition of building sector (Sorrell 2015; Wada et al. 2012). In the IEA scenario, relative contribution of the building sector to direct and indirect emissions become smaller from a third of global energy-related CO_2 emissions today to one-fifth in 2050 mostly as a result of electrification in space heating and cooking (IEA 2019f). In the 1.5°C scenarios, the share of combustible fuels in energy consumption of the buildings sector decreases to around 20% (Luderer et al. 2018).

Mitigation options in the future mobility 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 behaviour such as modal shift to public transportation and using car-sharing services. EV, FCV and bio-fuels are expected to increase to meet higher transport demand in SSP5, while the low transport energy demand is expected in the SSP1 (Bauer et al. 2017). EV accounted for more than 2% of global car sales in 2018, and three-out-of-four cars on the road are electrified by 2050 in the IEA scenario (IEA 2019f). Due to the difficulty in electrifying for freight, aviation and shipping, combustible fuels in energy for transportation still remains in 2050 even in the 1.5°C scenarios (Luderer et al. 2018). Transportation sector becomes the second largest contributor of energy-related CO_2 emissions by 2050, whose share rises to 35% from 25% of today, (IEA 2019f).

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, utilization and storage (CCUS) to utilization of hydrogen. Energy intensive industry, particularly iron and steel, cement and chemicals sectors, usually involves high temperature processes that are difficult to electrify (Gambhir et al. 2019; Luderer et al. 2018). Electric arc furnace in steel production is an alternative technology, but availability of scrap could be its main bottleneck to be a viable option (Oda et al. 2013). The low-temperature process heat requirements are mostly electrified or switching fuels to biofuels in light industry sub-sectors. The industry sector is the largest emissions contributor and constitutes about 40% of global energy-related CO_2 emissions by 2050, compared with 25% today because the transport sector electrifies more quickly than the industry sector (IEA 2019f).

The impacts of moving from a 2°C to a 1.5°C target are burdensome for energy system. Since the mitigation potential for non-CO_2 GHGs is already exhausted in the 2 °C scenario, additional efforts need to be made by reducing CO_2 emissions mainly in the energy sector. In addition to more rapid decarbonization of energy supply, further efforts are required in the hard-to-abate industry, transport and building sectors with expensive technological options or societal behaviour change (IEA 2019f; Rogelj et al. 2015a, 2018b). Abatement potential of remaining fossil CO_2 emissions is quite limited and the feasibility of reducing residual emissions depend on the technological innovation and social acceptability of large scale CDR deployment (Luderer et al. 2018).

6.6.4.4 Energy systems beyond net zero emissions

After energy systems become carbon neutral, additional mitigation may be required to limit temperature change. In many scenarios, energy sector CO_2 emissions become negative in the second half of the century through the use of carbon dioxide removal (CDR) technologies (Clarke et al. 2014). CDR technologies are a prerequisite particularly in the case of delayed action or locked in fossil-based energy system. 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). Even in pathways with limited BECCS, there remain certain amount of BECCS, implying that the development of CDR options remains an important strategy (van Vuuren et al. 2018). Negative emission technologies associated with the energy sector include BECCS, and direct air capture and storage (DACCS), completing a set of CDR options outside of the energy sector such as afforestation and reforestation, biochar, soil carbon sequestration, enhanced weathering on land and in oceans, and ocean fertilization (Haszeldine et al. 2018; Minx and Lamb 2018). BECCS is prevalent in 1.5°C and 2°C scenarios partially because IAMs put less weight to future BECCS costs due to discounting future economic value (Obersteiner et al. 2018; Anderson and Peters 2016); but it is also prevalent because IAMs have not traditionally included other means of CDR such as direct-air capture. CDR is not only used to obtain overall net negative emissions. It is also used to achieve net zero emissions in offsetting emissions from hard-to-abate sectors, such as the iron and cement industry, or aviation (IEA 2019f).

Stricter climate targets tend to require larger volume of CDR deployment. Cumulative gross negative CO_2 emissions between 2011 and 2100 are reach 550 (200-750) Gt CO_2 for the 2°C scenarios and 650 (450-1000) Gt CO_2 for the 1.5 °C scenarios (Rogelj et al. 2015a). The CDR requirement has variation across future socio-economic development. For 1.5 °C scenarios, lower final energy demand and baseline emissions in SSP1 are associated with the lowest BECCS deployment over the twenty-first century 150–700 $GtCO_2$, compared to 400–975 $GtCO_2$ in SSP2 and 950–1,200 $GtCO_2$ in SSP5 (Rogelj et al. 2018b). With limited carbon budget, delays in mitigation action require more rapid reductions, earlier net zero emission and larger scale deployment of negative emission technologies.

The viable energy-sector CDR options depend on the configuration of future energy systems (Waisman et al. 2019). Direct air carbon capture and storage (DACCS) has a high sequestration efficiency of 75-100% but has high energy demands and significant capital investment. These features are compatible with energy systems that produce constant output based on nuclear, fossil fuels with CCS, and renewable. BECCS is less capital intensive but requires substantial land area to produce bioenergy despite a relatively low sequestration efficiency of 50-90%. The advantage of biomass is its versatility in producing electricity, fuels, and hydrogen. BECCS system is valuable for sectors that are hard to decarbonize, such as transportation sector due to its current dependence on liquid fossil-based fuels (Creutzig et al. 2019b).

Recent publications (Fuss and Et al 2014; Smith et al. 2016a; Heck et al. 2018) raise concern about the broader political and economic feasibility in relying on large-scale deployment of negative emission technologies (NETs) to achieve Paris targets. NETs also involve risks not to be delivered on the scale as expected. Due to limited availability of land, large-scale deployment of bioenergy-based CDR technologies may have an impact on food production and biodiversity, which generate concern about the conflict with other sustainable development goals.

There are many types of negative emission technologies, but any single negative emission technology is unlikely to deploy at large scale due to concern about sustainability. Alternatively, holding a portfolios of different negative emission technologies to deploy each of them at modest scale could be a viable strategy (Minx et al. 2018). In the context of intergenerational equity and environmental integrity, early deployment of negative emission technologies is suggested to minimizes stranded assets and the risk associated with temperature overshoots (Obersteiner et al. 2018).

Box 6.20 Taking stock of the energy system transition

[Placeholder for SOD--This is placeholder text that indicates the issues we will address in the context of the global stocktake. The goal will be to discuss how to think about the three Talanoa questions in the context of energy system mitigation. We intend to emphasize that the stocktake is not just about where we are but also where we need to go and how to get there, and we intend to emphasize the need for an assessment of barriers and enabling factors.]

The Global Stocktake is a regularly occurring process in which efforts will be made to understand progress on, among other things, global mitigation. It is useful to frame the stocktake in terms of the three questions that are associated with the Talanoa Dialogue: where are we, where do we want to go, and how do we get there? These questions form the framing for consideration of progress in the context of the global stocktake.

Within each of these three questions, there is a broad set of indicators that could be used to measure progress, long-term goals, and near-term transitions. One set of data is associated with indicators that one might see as part of a statistical yearbook on emissions, energy, the economy, and land use. Examples would include CO_2 emissions from fuel combustion, energy demand by fuel, electricity demand by source, carbon intensity, energy intensity, the shares of specific technologies in the energy system. electrification rates. Forward-looking indicators might include those associated with technology costs and performance. A number of sources are available to develop this information in both national and global contexts, including this assessment, national reporting, a wide variety of databases of energy statistics (e.g., IEA), and official mid-century strategies. While most information may focus on where we are today, the mitigation pathways literature and mid-century strategies provide information regarding where do we want to go and how we get there.

While these technoeconomic indicators are critical elements of any efforts to take stock of the energy system, they do not address the broader societal issues that are essential to energy system transitions. Questions about the status of key mitigation-related energy policies such as energy taxes and subsidies, technology standards, or carbon markets are essential for understanding progress. More complicated is the assessment of barriers and enabling factors associated with the energy transition. These may include linkages to broader societal priorities such as energy access or economic development or the distributional effects of phasing out fossil fuels. These broader societal factors will be a critical element of any energy system stocktake.

6.7.2 Investments in Technology and Infrastructure

This section addresses the energy system investment needs associated with meeting Paris goals and regional difference in energy system investment. Implications of shifting investment patterns in energy systems are also discussed.

6.7.2.1 *Investment needs for low carbon energy systems*

Total investments in the global energy system were over US$1.8 trillion in 2018. This amounted to over 2% of global gross domestic product (GDP) and 8.6% of gross capital formation in that year. Fossil-fuel related investment, including oil, gas, and coal extraction plus fossil-fuel based generation was still the majority of the investment amounted to US$0.93 trillion, whereas renewable-related investment was about US$0.33 trillion in 2018. Currently global investment in low-carbon energy, including efficiency, and electricity networks was around US$0.9 trillion per year, but it needs to be expanded significantly to meet Paris target (IEA 2019h).

The growth of future energy demand boosts overall levels of global energy investment. Additional investment could be incurred to make energy systems low carbon. Average annual energy investment needs over the 2016-2050 period in the SSP2 are about US$2.5(1.9-3.0) trillion per year for the baseline scenario. There are US$3.0 (2.1-4.1) trillion investment needs annually for the 2 °C scenario and US$3.4 (2.4-4.7) trillion for 1.5 °C scenario, which are larger by 22% and by 36% respectively compared to the baseline scenario. With regard to a share of global GDP, the total energy investments account for 2.5% (1.6–3.4%) in the 2 °C scenario and 2.8% (1.8–3.9%) in the 1.5 °C scenario (McCollum et al. 2018b). Energy investment needs increases as climate targets become more stringent due to heavily reliance of more capital-intensive low carbon energy options. Another study shows overall energy investment requirements for the transition to a low-carbon energy system is about US$3.43 trillion per year over the 2015–2050 period on average with US$ 0.77 trillion of the incremental investment needs associated with the transition and US$ 2.66 trillion of the reference case of investment (Gielen et al. 2019). IEA's estimate is generally consistent with these assessments above. The Sustainable Development Scenario that correspond to well below 2 °C scenario reveals that total energy investment approximately amounts to US$3.2 trillion each year from 2019 to 2040 on average, increasing by more than 70% from today's level, although part of this additional investment is counterbalanced by reduced fuel costs (IEA 2019f).

The sectoral breakdown of investment, however, provides mixed picture. Power supply investment increases from US$0.8 trillion today to US$1.2 trillion per year between 2018 and 2040. The largest increase in supply side investment comes from renewables-based power generation, which adds up to US$0.5 trillion each year over the period between 2019-2030 and over US$0.7 trillion between 2031-2040 respectively. Investment in fossil fuel power generation still continue, but about half of this spending is associated CCUS technologies. Demand-side investment reach about US$1.2 trillion, which is more than three-times higher than today's level. Especially energy efficiency improvement in the buildings sectors, such as more efficient appliances, thermal insulation and efficient lighting, and the transportation sector which shift towards EV needs large amount of investment (IEA 2019f).

There are remarkable differences across countries in terms of basic energy needs, energy supply structures and consumption patterns, which affects the clear divergence in their investment landscapes (IEA 2019f). Currently 90% of energy investment is concentrated in high- and upper-middle income countries, but investment needs to grow for the fast-growing energy needs in lower-middle and low-income countries. The investment to ensure universal energy access, especially for electricity access, amounts to some $45 billion per year between 2019 and 2030. (IEA 2019f) Low energy expenditure is associated with high and increasing economic growth rates (Fizaine and Court 2016; Zhou et al. 2019a). Efficiency investment is important to minimize energy expenditures without hindering economic development.

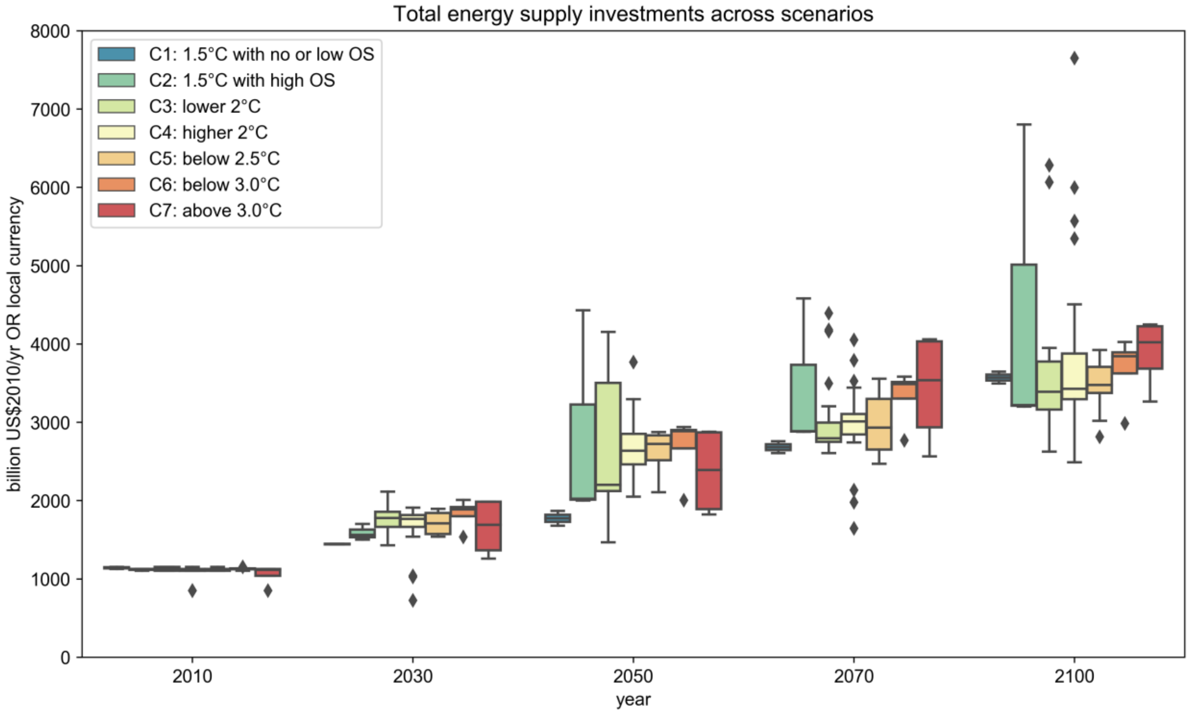


Figure 6.36 Total energy supply investments across scenarios (Source: AR6 Scenario Satabase)

Addressing the barriers of investment facilitate access to financing for climate technologies. There is a wide range of barriers in low carbon investment, such as currency and political risks, competition with other investment needs, and lack of knowledge. Removing these barriers could help mobilize finance (Hafner et al. 2019). About US$5.9 trillion per year of investment in infrastructure is required between 2015 and 2030 in the base case scenario and additional US$0.3 trillion per year of investment is required for the development of low-carbon infrastructure (Granoff et al. 2016). In light of the current annual fixed capital investment of US$ 26.7 trillion, the infrastructure spending gap is not attribute to lack of capital in the global economy, suggesting this additional US$0.3 trillion gap is covered by shifting existing capital investment to low-carbon investment in the larger context of fixed capital formation rather than the limited scope of climate finance. Increasing low carbon investment primarily require shifting existing capital investment (McCollum et al. 2018b; Granoff et al. 2016), not creating new pools of capital.

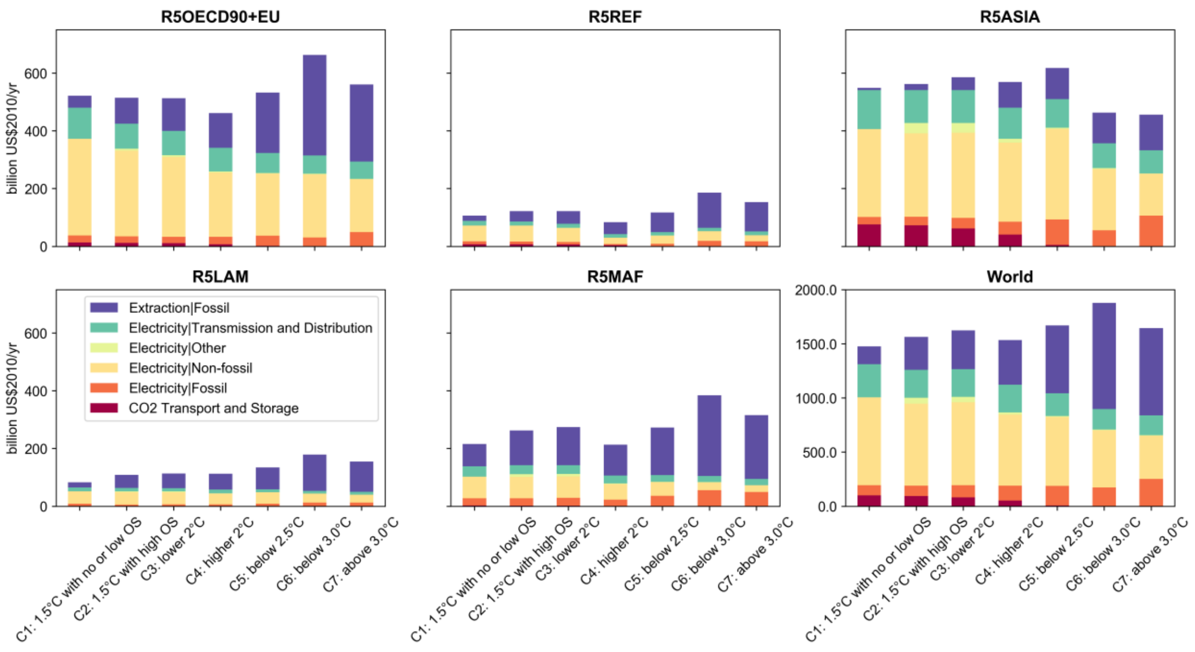


Figure 6.37 Annual average energy investment for fossil fuel supply, renewables, grid, energy demand, energy efficiency, and the other by region] (IPCC Scenario Database)

Involvement of private sector is essential to scale up low carbon investment for energy systems transformation, but private investment doesn't go mitigation project without enabling environment (Zhou et al. 2019a). In order to mobilize private capital, development of attractive conditions for low-carbon investments is crucial, especially countries where investment risks are high (Schmidt 2014). Despite huge variation in risk profiles across countries, most of 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 considerable impact on the assessment of investment profiles. Instead of the assumption of uniform risk, non-uniformities in investment risks lead to a 36% reduction globally in investments in low-carbon technologies whereas fossil-fuel investments increase by 11% (Iyer et al. 2015). 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 in terms of the life-cycle costs, while fossil fuel-based plants are dominated by fuel cost (Schmidt 2014). Climate policy to decrease such downside risks could help redirection of investment flow from fossil fuels to renewables.

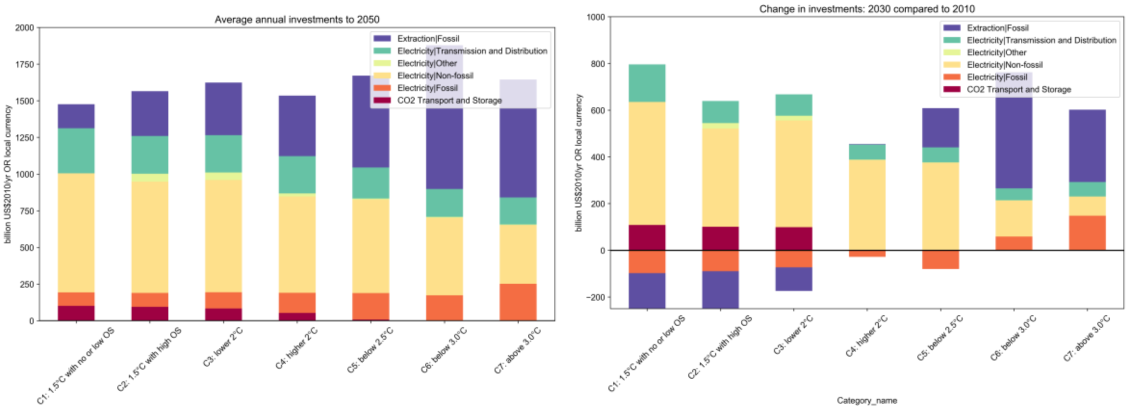


Figure 6.38 Left: Annual average investments period 2010-2050. Right: Change in investment profile, 2030 compared to 2010. (IPCC Scenario Database)

6.7.2.2 *Implications of energy transitions*

Climate change investments towards the Paris Agreement have both positive and negative impacts on other SDG targets. Switching to fossil fuels reduces air pollution and has positive health effects. On the other hand, an increase in energy prices and food prices due to land use change would adversely affect energy access and food security.

Shifting energy investment portfolio for delivering rapid decarbonisation in the economy has global distributional impacts (McCollum et al. 2014). Rapid phase-out of fossil fuels could cause economic and political instability in some states and institutions as a result of stranded assets (Gambhir et al. 2019). Currently, a huge amount of investment is made on fossil-fuels, but climate policies could induce technological transitions, which leave fossil fuel assets stranded. Shrinking fossil fuel markets and dropping fuel prices could bring about a discounted US$1-4 trillion wealth loss for producer's economy whereas importing countries has moderate positive effects on GDP (Mercure et al. 2018; Bednar et al. 2019). Lower demand of fossil fuels put downward pressures on the fossil fuel prices. IEA compares a higher fuel prices scenario whose oil prices settle in a $90-110/barrel range with a lower fuel prices scenario with a $60-70/barrel oil prices range to assess the impact on the hydrocarbon-dependent economies. The analysis shows that lower oil prices could cause a cumulative $7 trillion loss in revenue of these countries over the period to 2040, which translates into a drop of $1,500 annual disposable income per person(IEA 2018b). Such economic downturn could evolve large current account deficits, currency depreciation and lower government spending.

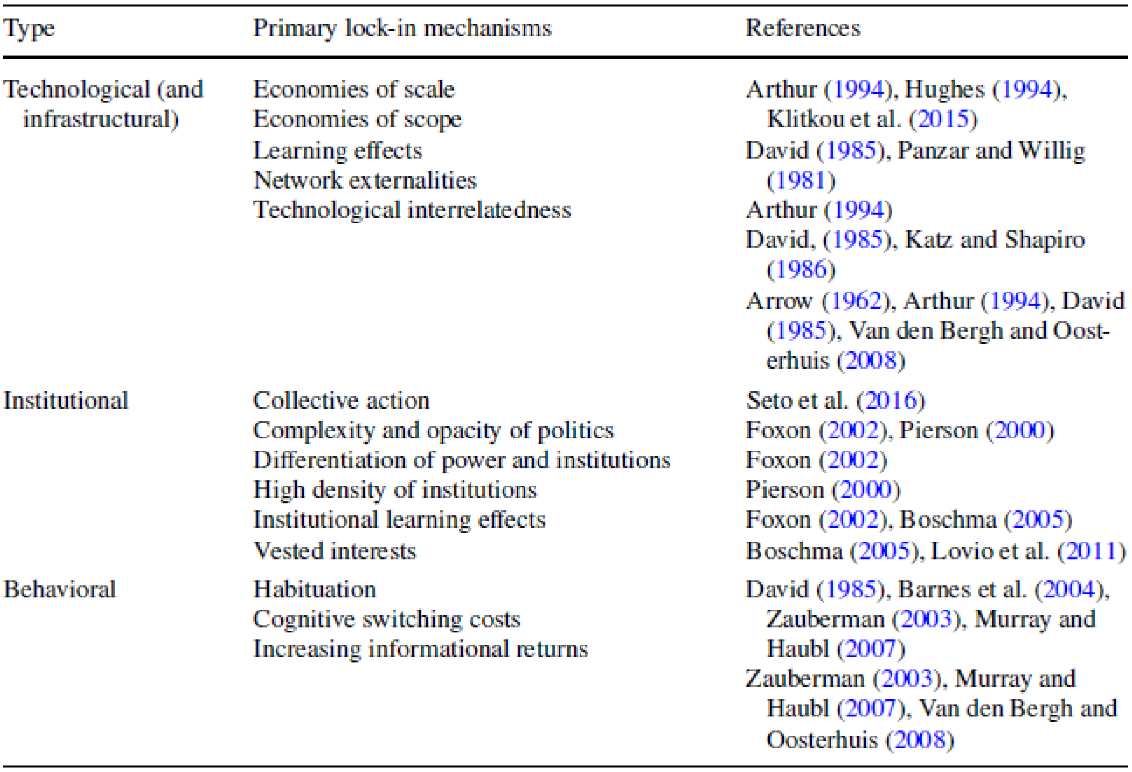
Stringent mitigation actions entail a major job reallocation. Jobs could shift from emission-intensive sectors, such as mining, chemical, steel, and cement, to low-carbon industry. Global job creation in renewable energy technologies is not sufficient to compensate for the employment reduction in the entire power sector for the 2 °C-consistent scenario (Vandyck et al. 2016a). The surge of low carbon technologies implies the plunge of fossil-based energy system (IRENA 2019f). If some fossil-fuel producers cannot manage rapidly falling demand, shifting investment pattern could be a potential factor of political instability for vulnerable commodity-dependent economies (Goldthau et al. 2019). Adequate attention to avoiding potential conflicts resulting from falling fossil-fuel demand is required for smooth transition to a sustainable energy system.

Most IAMs focus on technological and economic factors with little attention to institutional, behavioural and social aspects. These aspects, however, have impacts on deployment technologies. The social acceptance of nuclear power and CCS is crucial for expanding these technologies. Non-technology drivers are also key enablers for climate investments (Waisman et al. 2019). Individual behaviour shape green energy demand and affect investments in new energy technologies (Niamir et al. 2019).

6.7.3 Energy System Lock-In and Path Dependence

Lock-in refers to the inertia in systems that presents challenges in changing course. Given that energy system mitigation will require a major course change from recent history, lock in 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 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*

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, 2018). Such strong path dependencies – even in early formative conditions – can exercise lasting impacts on sociotechnical systems, producing inertia which can cut across technological, economic, and political dimensions (Vadén et al. 2019).

However, while much literature emphasizes the ability for path dependence to occur on the "supply side", via the sunk costs and legacies of material transport or energy supply systems, (Kanger et al. 2019) emphasize it can occur on the "demand side" as well, across user, business, cultural, regulatory, and transnational dimensions. (Kanger et al. 2019) argue that embedding or path dependence in user environments goes beyond purchase activities and can involve the integration of new technologies into user practices and the development of new preferences, routines, habits and even values. Embedding or path dependence in the business environment can shape the development of industries, business models, supply and distribution chains, and repair facilities. Embedding in 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. Embedding in the 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. These dimensions of path dependence suggest that technological diffusion is an active and contested process, full of choices, debates, and struggles across a variety of dimensions and scales. Such elements of path dependence can all co-evolve to reinforce particular socio-institutional structures and constituencies. As shown in (Kotilainen et al. 2020), these can all shape technology and infrastructure but also institutions and collective behaviour.

(Geels et al. 2018) note that due to lock-in dynamics, radical low carbon innovation involves systemic change. This extends beyond purely technical developments to include changes in consumer practices, business models and organisational arrangements. Radical low carbon innovation involves cultural change: Low carbon innovations are typically less attractive than energy supply innovations, and garner less interest from policymakers and the wider public. Most people have little interest in demand reduction and the economic incentive to save energy is often weak. An energy "revolution" will therefore require dedicated campaigns to create a sense of urgency and excitement about low carbon innovations. To alter cultural preferences, such campaigns need to go beyond information provision and aim to create positive discourses and increase competencies and confidence among (potential) users. Radical low carbon innovation involves new policies and political struggles: Since many of the benefits of low carbon innovation can be considered a public good, incentives may be weak in the absence of collective action. The development and adoption of low carbon innovations will therefore require sustained and effective policies to create appropriate incentives and support. The development and implementation of such policies entail political struggles because actors have different understandings and interests, which give rise to disagreements and conflicts. 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. Radical low carbon innovation involves pervasive uncertainty: The technical potential, cost, consumer demand and social acceptance of new innovations are highly uncertain in their early stages of development, which means that the process of radical innovation is more open-ended than for incremental innovations. 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 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.

6.7.3.2 *Physical Energy System Lock-In*

Continued exploration of fossil fuels, as well as commissioning of infrastructure reliant on it would tend to overcommit carbon emissions and may induce significant risks to achieving Paris Agreement goals. Despite projected needs to reduce fossil fuel usage and the multi-faceted benefits arising out of such phaseout, both coal and gas power plants have continued to commissioned globally ((Jewell et al. 2019); Section 6.3). In many cases, they are not only incompatible with the Paris Agreement goals but also may exceed the needed capacity in certain regions (Shearer et al. 2017).

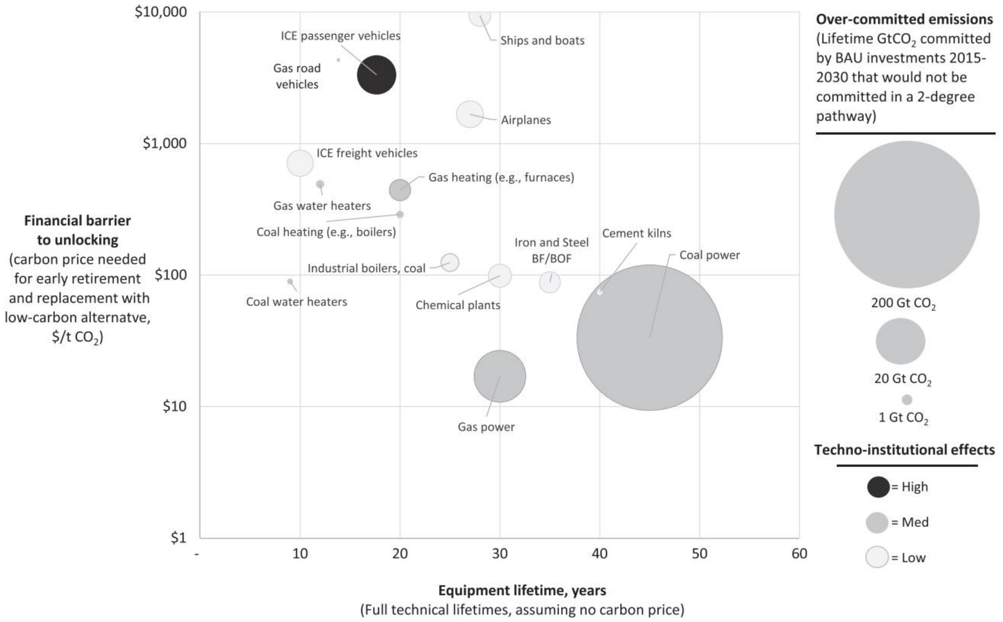


Figure 6.39 Global assessment of carbon lock-in risks by fuel and sector (Erickson et al. 2015).

A variety of estimates for the locked-in carbon have been presented for fossil-reliant infrastructure. By various accounts, around 200 Gt-CO$_2$ and 20 Gt-CO$_2$ are locked in within existing coal and gas power plants respectively (Erickson et al. 2015; Pfeiffer et al. 2018). Considerable locking in of carbon emissions (80-100 Gt-CO$_2$) is also found in the transport and heating sectors, albeit with somewhat lower lifetimes as shown in Figure 6.39. Further, coal-fired power plants that are currently under construction or planned for the future are associated with an additional ~300 Gt-CO$_2$. Even aside from the infrastructural investments, attention has been given to the fact that both coal and gas exploration have continued with permits 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). In terms of fuel production, it is projected that higher-cost, yet-to-produce resources, are most likely to increase carbon lock-in. This must lead to further scale back capital-intensive oil investments and especially to a substantial scale-back of capital investment in onshore tight oil production (Erickson et al. 2015). Without further action, all CO$_2$ emissions permitted in the 2°C Scenario will be “locked-in” by existing energy system infrastructure. The world’s existing infrastructure is already 846 Gt-CO$_2$, which exceeds the 1.5°C carbon budget and is slightly smaller than the 2°C one as shown in Figure 6.40 (Pfeiffer et al. 2016; Tong et al. 2019).

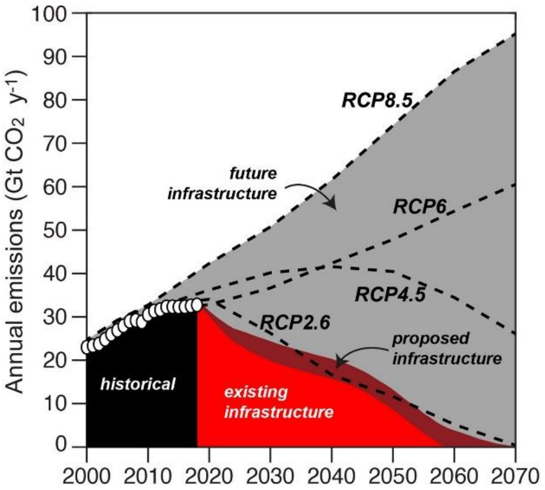


Figure 6.40 Annual emissions from existing, proposed and future infrastructure (Tong et al. 2019).

If stringent policies are untimely introduced for reducing carbon lock-in, it may help in meeting climate goals but will cause large-scale of stranded assets from early retirement, underutilization of capex and unburnable fossil fuels (Rozenberg et al. 2018; Kalkuhl et al. 2019). Implementation of near-term stringent GHG mitigation policies and also risk free returns to business investments are likely to be most effective in dealing with carbon lock-in. If such policies are implemented with significant delay, the continued deployment of fossil fuel reliant infrastructure might continue, and then prematurely retired. The global wealth loss in such a case is projected to be $ 1-5 trillion with clear regional disparities (Dietz et al. 2016; Mercure et al. 2018; Tong et al. 2019). This means that instead of the usual 50-60 years lifetime, plants may have to prematurely retire at 35 years in a well-below 2 °C scenario or 20 years in a 1.5 °C scenario (Cui et al. 2019). Similarly, with the fuel reserves, it is projected that 50% of gas and 80% of coal reserves will remain unburnable up to 2050 if warming is to be restricted to 2°C (McGlade and Ekins 2015).

Accordingly, current investment decisions are critical because there would be limited room within the allotted carbon budgets of 2°C. Currently, a number of strategic choices may be made to reduce the locked-in carbon within large-scale infrastructure such as power plants. This includes reduction of subsidies to fossil fuels, making upcoming plants ready for CCS or appropriately designed for fuel switching. Alternatively, scenarios involving large lock-in may necessitate considerable deployment of NETs.

On the power sector front, the scale of stranded assets could be reduced through inclusion of CCS in the portfolio (Byrd and Cooperman 2018). Various works globally have quantified the role of CCS in terms of rescuing stranded assets of the order of hundreds of gigawatts (Clark and Herzog 2014; Fan et al. 2018). Moreover, these studies also demonstrate the role of strong policy choices to facilitate CCS transitions within power plants in the short-term such that the costs of CCS from a bottom-up perspective are less. Figure 6.41 shows the role of CCS in helping avoid large scale stranded assets. Unabated fossil fuel does decline in all scenarios by significant margins below renewables but has some presence countered by NETs but some studies rely on totally zero-carbon scenarios. With inclusion of CCS, transitions show presence of fossil fuels in energy mix and transitions also become more economical. Moreover, CCS as a tool may enhance negative emission transitions if co-firing is gradually introduced into systems (Lu et al. 2019).

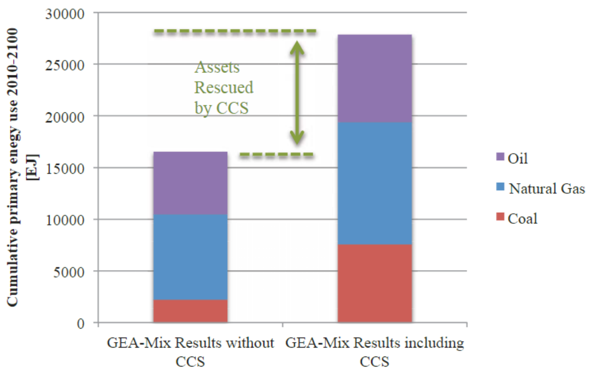


Figure 6.41 (Mockup) Total primary energy use from 2010-2100 from fossil fuels in all sectors for the GEA-Mix scenarios (Clark and Herzog 2014). It could be possible to arrive at a range by considering ensemble of IAMs which would enable us to calculate the rescued assets.

Apart from the power sector, there is considerable lock-in in the urban sector through buildings and transport. For some aspects (e.g. individual vehicles), the socio-institutional effects are strong. Therefore, resolving lock-in in the urban sector is considerably more complicated. Here, long-term improvements would entail significant non-technological challenges as well with behavioral change issues involved with the society (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 behavioural lock-ins (Ürge-Vorsatz et al. 2018).

Designing policy for avoiding lock-in needs to account for role of time; that is incorporating the differences between short-term and long-term interventions. This is because individual interventions that might enable behavioral changes in the short-term must be compatible with larger industrial scale policy changes are necessary for major R&D breakthroughs in the longer-term to catalyze clean energy innovation (Seto et al. 2016). Such policies would also be different such that developed and developing countries need to approach energy transitions as a results of different resources and carbon budgets (Bos and Gupta 2018; Lucas 2016).

Past and present energy sector investments have created technological, institutional and behavioral path dependencies aligned towards coal, oil and natural gas. 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). Of particular interest are countries that invest in large projects to provide energy to stimulate economic development and reduce poverty, but at the same time facilitates strong and long-lived path dependence, due to technological, infrastructural, institutional and behavioral lock-ins.

Path dependencies may be positive, such as introducing energy security, reduced cost of electricity and high employment rate. On the other hand, several coal mining communities, for instance, have significant health and economic burdens thus creating incentives for decarbonization. Here, it is also notable to taking into account recent facts and trends concerning the dramatic changes in some countries that have also impacts in the building of energy infrastructure.

6.7.4 Fossil fuels in transition

The overarching question pertaining to fossil fuels in transitions is whether there is a role for fossil fuels in the various pathways in light of requirements for large-scale decarbonization targets. In various pathways for a 2°C scenario, unabated fossil fuel consumption declines in all scenarios by significant margins below renewables and BECCS (Kriegler et al. 2018b; van Vuuren et al. 2015; Gambhir et al. 2015). While some scenarios exhibit some continued usage countered by aggressive negative emissions, others analogous to “sustainable pathways” within the deep decarbonization project totally zero-carbon energy technologies (Bauer et al. 2015; Bertram et al. 2018; Grubler et al. 2018). Further, reductions are increasingly marked as stringency of the underlying climate policy increases as shown in Figure 6.42.

While some regions have demonstrated coal phase out with dedicated policies to initiate these ((Jewell et al. 2018); Box on Coal Phaseout Examples), there is also a trend of increased number of coal plants in other regions (with delayed peaking of coal use). Similarly, natural gas power plants have rapidly scaled up made possible by large unconventional gas developments (Kriegler et al. 2018b; van Vuuren et al. 2015) exacerbating risks of large fugitive methane leakage. This is directly in contrast with the pathways shown in the literature, where it is observed that in various pathways for a 2ºC scenario, unabated fossil fuel consumption does decline in all scenarios by significant margins below renewables. Fossil fuel transitions have been made significantly difficult due to concerns for energy security and import dependence. Coal seems to have dug in its heals against climate change, for at least a decade riding on energy security and affordability concerns (Garg and Shukla 2009; Jewell et al. 2016). Rising geopolitical risks could make international oil markets more volatile with widespread fluctuations in oil and gas prices being seen in the last five years (Plakandaras et al. 2019; Beccue et al. 2018).

For adhering to the 2°C targets, there is need for change in the directions of fossil fuel investments. Accordingly, three types of fossil fuel transitions are noted in the literature, as we describe below.

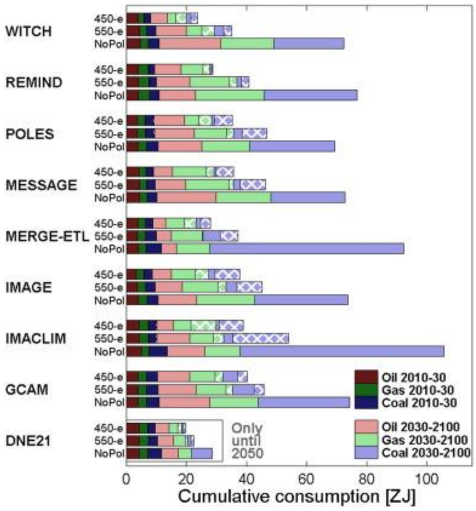


Figure 6.42 Cumulative consumption of fossil fuels in various IAM results adhering to various scenarios. [Placeholder-This figure will be modified based on the AR6 database.] Source of this figure is (Bauer et al. 2015).

The first mechanism is to increase levels of CCS deployment in the upcoming decade. It is noteworthy that radically larger carbon prices are required for similar targets when CCS is not in the energy mix (van Vuuren et al. 2016). As inclusion of CCS increases, transitions do show presence of fossil fuel energy usage and also become more economical (Muratori et al. 2016; Marcucci et al. 2019). Thus, inclusion of CCS affects not just the climatic viability of continued fossil fuel usage but also the overall investment required towards achieving major climate targets.

Having said that, there are differences in the perceived role of CCS in facilitating transitions for a variety of issues including uncertainties in costs of CO_2 capture, degree to which CCS may mature technologically and ethical dimensions pertaining to longer-term fossil fuel use and reliable sequestration of CO_2. Even when these differences are not considered, there are differences as to how CCS is treated amongst various models. For instance, some studies show CCS to be significant in energy mix (Koelbl et al. 2014b; Eom et al. 2015) while others do show limiting factors to CCS deployment that could include residual emissions (Budnis et al, 2018). Technology learning along with fuel pricing in CCS (see section 6.4) is shown to be important for not just long-term climate objectives (Muratori et al. 2017) but also in alleviating welfare losses (Huang et al. 2017). This may also relieve large investment needs which can be a major deterrent to CCS deployment (Koelbl et al. 2014a).

The second major aspect as it pertains to fossil fuel transitions is the differentiated role of coal and gas, as arising from differences not just in GHG emissions but also end-use flexibility, air pollution and other externalities (Wilson and Staffell 2018). In the SSP-5, it is noted that gas displaces coal beyond 2050 across scenarios (Kriegler et al. 2017). Such transitions can be encouraged through market-based, non-market based or complementary policy instruments which are appropriately managed, such as not to induce leakages. There is broader agreement in global models that coal decline is less susceptible to leakage and other regional effects but ambiguity in understanding if gas switching is associated with aggressive or less-aggressive targets based on regionality. Comparing to coal, oil and 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 organizations call for a transition away from oil. This work also addresses the so-called unburnable fossil fuel paradigm, which is also showing monotonous trends though with widespread regional variability. Generally, coal is unburnable with high certainty (McGlade and Ekins 2015) with other work showing large oil/gas exhaustion (Bauer et al. 2016c) potentially based on climate ambitions (Cherp et al. 2016). Note that these differences are not only present in the power sector but also in other end-use. Unprecedented growth is projected in the liquefied natural gas (LNG) market especially with the developments in transnational natural gas pipelines (Vivoda 2019).

While comparing coal and gas on multiple accounts (GHG, costs, air, water) does show an increasing trend towards the latter, there are considerable risks with heightened gas production. As discussed in Section 6.4, large fugitive methane emissions have been noted in particular regions of unconventional gas development, which may reduce the viability of such transitions. Thus, while some life-cycle studies conclude definitively for coal to be better than gas in GHG implications (Mallapragada et al. 2019; Wilson and Staffell 2018), others define leakage as critical parameter (Qin et al. 2017; Tanaka et al. 2019; Grubert and Brandt 2019).

Finally, "sustainable transition" pathways have indicated a complete fossil phaseout which could entail numerous other co-benefits. For instance, fossil fuels generate are estimated to generate 2.65 jobs per $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 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). 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. This has been catalyzed with increased number of pro-renewable policies, reduction of subsidies towards fossil fuels and significant cost-reductions in solar and wind power.

To enable technologically efficient transitions, renewable energy technologies would require significant upgradation. Most importantly, energy storage would be required to implement renewables as baseload (to reduce duck curve phenomenon), along with widespread usage of net metering and other approaches. It is projected that the costs of renewable energy storage would decline by about a third by 2030 and up to a half by 2050, which would replace of fossil power plants as the baseload (Box on energy storage; (Schmidt et al. 2019)).

6.7.5 Policy and Governance

Public policy interventions and governance frameworks are key for shaping near and medium term energy system transitions. 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 (see (Kriegler et al. 2014), for a description of Shared Climate Policy Assumptions used in SSPs).

Academic research focuses mainly on market-based approaches as the least-cost policy to achieve emission reductions (Kube et al. 2018). However, countries have implemented policy mixes with a diverse set of complementary policies to achieve their energy and climate policy targets. A prominent example is the implementation of 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). The NDCs under the Paris Agreement also describe fragmented climate policy mixes.

Policy mixes have multiple causes: different policy goals and objectives (including political, social and technological influences), multiple market, governance or behavioural failures or previous policy choices of earlier policy eras (Rogge 2017). With multiple policy goals or some type of imperfection, well designed policy mixes can in principle reduce mitigation costs or increase welfare. (Corradini et al. 2018), for example, analyse the interaction between carbon taxes and the support for clean energy technologies in the EU clean low-carbon strategy. Complementary technology policies reduce mitigation costs and allow for the early adoption of more stringent climate targets (Vandyck et al. 2016b).

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). Policy mixes are often not "optimal". The evolution of new policy interventions out of pre-existing policies and the difficulty to address multiple policy goals and imperfections properly are only two reasons. Energy scenarios are rarely studying and acknowledging these interactions.

Most energy transition pathways from the literature are based on cost-optimal mitigation frameworks and without an explicit analysis of interactions between policy measures. Reductions are undertaken by economic sectors and regions with lowest marginal abatement costs and are consistent with uniform carbon pricing (e.g. (Vrontisi et al. 2018). Cost-optimal scenarios are also not describing real-world energy transitions properly (see (Trutnevyte 2016) for an assessment of the UK historic UK electricity system transition).

Instead of thorough analysis of policy mixes, energy transition scenarios analyse differences in implied carbon prices, constraints in technology deployment and timing of policies. Global mitigation costs for achieving NDC targets are reduced if uniform carbon prices are introduced through emissions trading (Fujimori et al. 2016). (Vandyck et al. 2016b) analyse the Paris pledges and a 2 degree scenario taking into account carbon prices, fuel standards for vehicles and feed-in tariffs for renewables. They found that current pledges imply differing carbon prices and assume convergence of carbon prices in their 2 °C scenarios.

Differentiated scenarios describe only cursorily how the assumed changes in emissions, efficiency levels or technologies are achieved and the underlying costs of policy mixes for energy transitions. (van Vuuren et al. 2018) analyse alternative scenario frameworks for achieving the 1.5 °C target. Scenarios with uniform carbon taxes are compared with scenarios that assume faster penetration of best available technologies for energy efficiency, higher electrification rates with penetration of variable renewables or lifestyle changes that lead to lower GHG emissions.

Scenarios for the medium term (e.g. until 2030) usually include a diverse set of agreed policies or foresee a continuation of policies and mandatory objectives. Sometimes, the impact of different ambition levels, e.g. regarding energy efficiency targets or renewable targets are assessed. (Capros et al. 2018) explore more ambitious energy efficiency targets for the EU until 2030 (-27 to -40%). Instead of stylized implementation of market based mechanism, concrete bottom-up policy measures like technology standards or specific transport and building policies are identified besides the use of the EU ETS. Looking at energy system costs until 2050, they identify the scenario with a 30% energy efficiffficency target as the most cost-effective among the scenarios.

Long term scenarios until 2050 often assume similar detail in policy implementation until 2030, but use stylized implementation of carbon price signals after 2030. The European Commission (European Comision 2018) compares eight energy and climate scenarios for 2050, which differ in the climate target and the options explored to reduce GHG emissions (energy demand reduction, different technological energy supply options, use of negative emissions). The pathways are almost identical until 2030, but differ in the long run. Beyond 2030, there is a stylised carbon price assumed in all scenarios and hence cost-effective technology deployment. The scenarios differ, however, by the assumption about coordinating policies targeted on infrastructure and research, development and innovation. Energy system costs depend strongly on the climate target. Some scenarios focusing on power-to-X and H2 pathways generate also high total system costs.

6.7.6 Behaviour and Societal Integration

Energy system transitions require some level of support from the societies in which they take place. Members of those societies, including individuals, civil society, and businesses, will all need to engage with and be affected by the transitions, and thus play a critical role into whether carbon neutral energy systems can be achieved. First, they need to be willing to adopt a wide range of mitigation behaviours. Such behaviour changes can be enabled and supported by a wide range of strategies and policy. Second, societal actors need to accept system changes, mitigation options and policies aimed to enable and support behaviour changes. Hence, it is important to understand which factors increase the likelihood that policies and system changes are acceptable to different actors in society.

6.7.6.1 Strategies to encourage climate mitigation actions

Climate policy would be more effective if it targets key factor inhibiting, enabling and motivating mitigation behaviour of different individuals and groups. As barriers may differ for different mitigation options and regions, and different groups may face different barriers to change, tailored approaches would be more effective (Grub et al., 2017). A wide range of policy approaches can be implemented to enable and strengthen actors' motivation to engage in mitigation behaviour, and to improve co-benefits of such actions, including education and informational campaigns, regulatory measures, financial (dis)incentives, and infrastructural and technological changes (Steg and Vlek 2009; Rosenow et al. 2017).

When people face important barriers to change (e.g., high costs, legal barriers), policy would be needed to enable and increase the attractiveness of low carbon actions, or to inhibit and decrease the attractiveness of behaviour associated with high carbon emissions. As people generally face multiple barriers for actions, combinations of policies are mostly more effective (Rosenow et al. 2017). For example, low-carbon technology may not be adopted or not be used as intended when people lack resources (e.g., finances, knowledge) or trustworthy information about the merits of the technology (Pritoni et al. 2015). Yet, current policy efforts to promote adoption of low-carbon technologies focus on economic incentives, and infrastructure and technological changes, and hardly target cognitive and motivational factors affecting mitigation actions, which may result in suboptimal effects as policies are likely to be more (cost-)effective when they systematically take such factors into account (Mundaca et al. 2019). Moreover, policy efforts focus on energy efficiency technologies with relatively low costs and complexity, but there seems a lack of policy instruments supporting deeper energy efficiency improvements that may be needed to meet ambitious climate targets (Rosenow et al. 2017).

Financial incentives can remove barriers to change and enable mitigation actions (Santos 2008; Thøgersen 2009; Eliasson 2014; Maki et al. 2016; Bolderdijk et al. 2011) and may be needed if mitigation actions are rather costly, such as in case of investments with high upfront costs (Mundaca 2007). Indeed, uptake of residential solar photovoltaics increased in many countries after the introduction of favorable financial incentives such as feed-in-tariffs, federal income tax credits, and net metering policies (Wolske and Stern 2018a). Also, a government subsidy promoted the installation of solar water heaters in Taiwan, although only in the initial stage (Chang et al. 2009).

Financial incentives may underperform expectations when other motivational factors are overlooked. For example, people may not respond to financial incentives (e.g., to promote energy efficiency) when they do not trust the organization sponsoring incentive programmes or when it takes too much effort to receive the incentive (Mundaca 2007; Stern et al. 2016). This suggests that financial incentives would be more effective when they are supplemented by strategies that address the nonfinancial barriers to action.

Communicating financial consequences of behaviour seems less effective than actually changing financial costs and benefits. Emphasising financial benefits of mitigation actions seems less effective than social rewards (Handgraaf et al. 2013) or emphasising benefits of actions for people (such as public health) and the environment (Bolderdijk et al., 2013b; Asensio and Delmas, 2015; Asensio and Delmas, 2016; Schwartz et al., 2015); emphasizing financial benefits of mitigation actions may even result in increased energy consumption (Delmas et al. 2013). Financial appeals had no added effect next to social comparison information, and may even reduce the effects of the latter (Pellerano et al. 2017). Effects of financial appeals may be limited because such appeals make people focus less on environmental considerations, can weaken intrinsic motivation to engage in mitigation actions and provide a license to pollute, thereby weakening non-financial motivates for engagement in mitigation behaviour (Agrawal et al. 2015; Bolderdijk and Steg 2015; Schwartz et al. 2015). In addition, pursuing small financial gains is perceived to be less worth the effort than pursuing equivalent CO_2 emission reductions (Bolderdijk et al. 2013b; Dogan et al. 2014).

Providing information on the causes and consequences of climate change or on effective mitigation actions mostly increases people's knowledge and awareness, but is generally not effective in promoting mitigation actions by individuals (Abrahamse et al. 2005) or organizations (Anderson and Newell 2004). Fear-inducing representations of climate change may even inhibit action when they make people feel helpless and overwhelmed (O´Neill and Nicholson-Cole 2009). Communicating lifetime costs of energy efficient products and appliances to clarify that their price premium can often be recouped over time through energy savings does not affect purchasing decisions (Allcott and Taubinsky 2015; Kallbekken et al. 2013). Yet, communicating fuel efficiency of a car in units that are intuitively understood increased the likelihood that people choose a more energy efficient car (Schouten et al. 2014). Energy-related recommendations and feedback (e.g., via performance contracts, energy audits, smart metering) can promote energy conservation, load shifting in electricity use and sustainable travel choices, particularly when framed in terms of losses rather than gains (Gonzales et al. 1988; Wolak 2011; Bradley et al. 2016; Bager and Mundaca 2017).

Yet, 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 organizations (Noll et al. 2014). Also, information is more effective when tailored to the personal situation of actors, when demonstrating clear impacts, and when resonating with actors' core values (Abrahamse et al. 2007; Boomsma and Steg 2014; van den Broek et al. 2017a; Daamen et al. 2001; Wolsko et al. 2016; Bolderdijk et al. 2013a). This may explain why home energy audits promoted household energy savings (Delmas et al. 2013; Alberini and Towe 2015), including investments in resource efficiency in buildings and renewable energy generation (Kastner and Stern 2015). Tailored information prevents information overload (Abrahamse et al. 2007; Goodhew et al. 2015), and people are more motivated to consider and act upon information that aligns with their core values and beliefs (Bessette et al. 2014; Bolderdijk et al. 2013a; Boomsma and Steg 2014; Hornsey et al. 2016; van den Broek et al. 2017b; Campbell and Kay 2014).

Energy use feedback is generally effective in promoting energy saving behaviour within households (Grønhøj and Thøgersen 2011; Fischer 2008; Karlin et al. 2015; Delmas et al. 2013) 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). Simple information is more effective than detailed and technical data (Wilson and Dowlatabadi 2007; Frederiks et al. 2015; Ek and Söderholm 2008). For example, energy labels (Banerjee and Solomon 2003; Stadelmann 2017), visualization techniques (Pahl et al. 2016), and ambient persuasive technology (Midden and Ham 2012) can encourage energy saving actions as they immediately make sense and hardly requires users' conscious attention. The effects of feedback on energy savings can be amplified if combined with price signals related to time-varying pricing (Newsham and Bowker 2010) or a conservation goal (Abrahamse et al. 2007; McCalley and Midden 2002); goal setting is most effective when realistic goals are set that are not too low or too high (Loock et al. 2013). Moreover, feedback can be provided to make people aware of their previous mitigation behaviours, which is likely to increase their environmental self-identity (Van der Werff et al. 2014), which can motivate people to act in line with this identity and to engage in other types of mitigation behaviour as well (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). For example, providing social models of desired actions can encourage mitigation action (Osbaldiston and Schott 2012; Abrahamse and Steg 2013; Sussman and Gifford 2013). Social comparative feedback that informs people about their own energy use relative to others can be effective (Nolan et al. 2008; Allcott 2011; Schultz et al. 2015), but it results in lower savings compared to other types of feedback (Karlin et al. 2015), and effect sizes are relatively small (Abrahamse and Steg 2013). Yet, such feedback can be easily administered on a large scale at low costs (Allcott and Mullainathan 2010).

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

Behaviour change can be initiated by governments at various levels, but also by individuals, communities, profit-making organizations, trade organizations, and other non-governmental actors (Stern et al. 2016; Lindenberg and Steg 2013; Robertson, J and Barling 2015). Bottom-up approaches can be effective in promoting mitigation behaviour (Abrahamse and Steg 2013). For example, community energy initiatives can encourage sustainable energy behaviour among their members (Middlemiss 2011; Seyfang and Haxeltine 2012; Abrahamse and Steg 2013), especially when community ties are strong (Weenig and Midden 1991). People not only become involved in such initiatives because they are concerned about the environment, but also because they are motivated to meet and interact with other people, suggesting that involvement in such initiatives may motivate mitigation behaviour among people who are less concerned about protecting the environment (Sloot et al. 2019). Governments could facilitate such bottom-up initiatives so that their potential effects can be optimised. Organisations can promote mitigation behaviour among their employees by clearly communication their mission to reduce the climate impact of their organization, and the strategies they implemented to achieve this mission (Ruepert et al. 2017).

Providing default options, in which case a preset choice is implemented if a consumer does not select another choice option offered, can encourage mitigation actions such as energy savings, green electricity uptake, energy saving lighting settings and meat-free meal 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 can shape, enable or prevent the transition to carbon-neutral energy systems. Public acceptability reflects the extent to which the public evaluates climate policy, mitigation options, and system changes in a favourable or unfavourable way. Some low carbon options are not evaluated very positively, including nuclear power and CCS, while other low carbon options are generally evaluated rather favourably, such as renewable energy sources (Steg 2018), although public acceptability may be lower if renewable energy sources are employed at a large scale, and generated in the vicinity of one’s neighourhood (Devine-Wright and Howes 2010).

To understand whether and how public concerns about climate policy and mitigation options can be addressed, it is important to identify which factors affect public acceptability. Public acceptability not only depends on the expected costs and benefits of policies or options, but also on how these costs and benefits are distributed across groups, whether fair decision-making procedures have been followed, and the extent to which people trust the agent implementing the policy or option.

First, public acceptability climate policy and mitigation options is higher when people expect more positive and less negative consequences of it (Demski et al. 2015; Drews and Van den Bergh 2016), including positive effects for self, others and the environment (Perlaviciute and Steg 2014). For example, public acceptability of energy system change depends on consequences for efficiency and wastefulness, environment and nature, security and stability, social justice and fairness, and autonomy and power (Demski et al. 2015). Public acceptability of a nuclear waste repository was lower when people expected negative health effects for locals (Sjöberg and Drottz-Sjöberg 2001), and public acceptability of a wind farm project was lower when people expected that only few farmers would benefit from it (Cass et al. 2010). 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 disrupts place-based attachments or threatens place-based identities (Devine-Wright 2009, 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 favourable than expected (Schuitema et al. 2010; Eliasson 2014; Weber 2015); effective policy trials can thus build public support for climate policy.

Second, climate policy and carbon neutral options are perceived to be more fair and acceptable when costs and benefits are distributed equally, and when nature, the environment and future generations are protected (Sjöberg and Drottz-Sjöberg 2001; Schuitema et al. 2011; Drews and Van den Bergh 2016). A fair distribution of costs and benefits can additionally improve the perceived legitimacy and effectiveness of energy and climate policies (McCauley et al. 2019).

Third, climate policy and mitigation options, such as renewable energy projects, are perceived as more acceptable and fair when transparent procedures have been followed, including participation by the public (Dietz 2013; Bernauer et al. 2016b; Bidwell 2014) or public society organizations (Bernauer et al. 2016b; Terwel et al. 2010), offering people the opportunity to have a voice, to express their opinion, threat them with respect, openness and honesty, and considering their interest and concerns seriously when decisions are being made (Dietz and Stern 2008; Perlaviciute et al. 2018; Evensen et al. 2018). People say they want to be informed and able to participate in decision making on climate policy and mitigation options (Devine-Wright 2005; Gross 2007; Terwel et al. 2012), and they favour decision-making processes (Arvai 2003; Walker et al. 2017), including the outcomes (Arvai 2003), that provided possibilities for public participation over those that did not. Public acceptability is particularly enhanced when people can influence major rather than only minor decisions regarding projects (Liu et al. 2019). Engaging the public in decision making on climate policies and mitigation options enables to bring in public knowledge and views that may otherwise be missed, thereby enhancing the quality and legitimacy of the end decisions (Bidwell 2016; Dietz 2013). Providing benefits to compensate 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 2010b; Cass et al. 2010), or feel they are being bribed (Cass et al. 2010; Perlaviciute and Steg 2014). Earmarking revenues of pricing policy is a way to compensate affected groups; earmarking revenues 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 pricing policies.

Fourth, public support is higher when individuals trust responsible parties (Perlaviciute and Steg 2014; Jiang et al. 2018; Drews and Van den Bergh 2016; Liu et al. 2019). For example, lack of trust in institutions inhibits acceptability of demand side management technology (Michaels and Parag 2016). Public support for unilateral, non-reciprocal climate policy is rather strong and robust (Bernauer et al. 2016a), and public support for unilateral climate policy is not lower than for multilateral policy (Bernauer and Gampfer 2015).

Public acceptability of climate policy and carbon neutral options differs across individuals, depending on their values, worldviews and climate beliefs. Climate policy and carbon-neutral energy 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 and hierarchical worldviews (Dietz et al. 2007; Perlaviciute and Steg 2014; Drews and Van den Bergh 2016). Similarly, public decision makers are more likely to accept climate change policy when they strongly endorse environmental values (Nilsson et al. 2016). Climate and energy policy is more acceptable when people believe climate change is real and when they are concerned about climate change (Hornsey et al. 2016); climate beliefs are particularly related to acceptability of climate policy when individuals have high political trust (Fairbrother et al. 2019). Furthermore, individuals are more likely to support climate and energy policy when they believe their actions contribute to climate change, think their actions would help mitigate 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

Energy is integral to both modern and traditional societies. This means that energy transitions can have pervasive effects that may be important broadly or to particular groups. Some of these may be perceived as costs, whereas others may be perceived as benefits. From the perspective of climate mitigation, these costs and benefits are essential in that they largely determine societal support for, or resistance to, mitigation. They can largely be understood in the context of sustainable development. This section discusses the costs and benefits of energy system transitions and, in doing so, addresses the links to sustainable development.

Sustainable development and its interlinkages with both energy and climate are extremely involved and diverse issues. Chapter 17 deals with multi-faceted issues of sustainability-energy-climate frontiers. Some of the key aspects discussed there are (1) interlinkages between mitigation and adaptation, (2) coherence between short-term and long-term mitigation, and (3) how energy transitions interact with multi-faceted goals such as air pollution reductions while managing economic risks such as stranded assets. In this section, we seek to cover other extensions of electrification-energy-sustainability interactions and provide some detailed archetypes on how transitions could create a balance between climate goals (NDCs, 2°C, 1.5°C) and SDGs.

One important metric for regarding energy system transitions is economic costs. The economic costs of meeting different goals depends on the stringency of the mitigation target, economic (fuel prices, energy service demands etc) and technological developments (technology availability, capital costs, operating and maintenance costs, levelised cost of energy of key technologies). In addition, required changes in infrastructure and behavioural patterns and lifestyles matter. Model based assessments vary depending on these assumptions and differences in modelling approaches (Krey et al., 2019).

Country characteristics determine social, economic and technical priorities for low-emission pathways. Domestic policy circumstances impact pathways and costs, e.g. when affordability and energy security concerns are emphasized (Oshiro et al., 2016) or when Sustainable Development Goals (SDGs) relating to energy access, energy security, air quality, poverty alleviation or employment creation are considered (Waisman et al. 2019). Moreover, the implementation of mitigation policies matters for economic costs, especially the mix of different stringent policies (incl. a combination of market-based instruments like emissions trading and taxes, regulation, subsidies, standards).

Carbon prices reflect the cost of mitigating at the margin and are found to be between 45–1050 USD2010 tCO_2-eq in 2050 under a Higher-2°C pathway and range from 245–14300 USD2010 tCO_2-eq for a Below-1.5°C pathway in 2050. Global average discounted marginal abatement costs across 1.5°C- and 2°C pathways differ by a factor of four across models (IPCC, 2018).

Total costs of shifting from a fossil-fuel based energy system towards a low-carbon energy system well-below 2°C are moderate (Ribera et al., 2015; OECD, 2017). Net costs are substantially reduced when accounting for reduced operating costs (especially fuel costs) and greater energy efficiency (Ribera, 2015). Incremental costs can be entirely offset provided integrated low-emission infrastructure investment. In the IEA 66% 2°C scenario a net impact on output on the average G20 country in 2050 of 2.5% above the baseline, i.e. a net growth effect, is estimated which rises to a total increases in output of 4.6% if avoided climate damages are taken into account (OECD, 2017).

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, 2017). A delay of decisive action would increase the costs of transition due to a larger stock of high-carbon infrastructure. Losses would materialize as soon as a more abrupt transition starts and become larger for net fossil-fuel exporting countries (OECD, 2017). In addition, technological learning can reduce costs as economies of scale create own momentum that further lowers costs and drives additional global deployment, as seen for declining solar PV costs to date (Ribera et al., 2015). International cooperation in climate mitigation reduces total economic mitigation costs and corresponding prices of carbon.

While economic costs are an important metric for evaluating energy system transitions, they are far from the only metric of importance for decision making. The most direct SDG pertaining to energy transitions is ‘access to clean and affordable energy’. This encompasses improvements in energy efficiency and infrastructure. Developing countries throughout South America, Northern Africa and Asia have noted differentiating levels of electrification, which has led to multiple benefits (Malakar 2018; Aklin et al. 2018). For instance, 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; Aggarwal and Toshniwal 2018)(Lam et al, 2016). Some additional positive trends have been noted in some Asian countries, where electrification has been obtained at lower income levels as compared to developed countries (Rao and Pachauri 2017).

Notwithstanding these changes in electrification patterns, one billion people still lack access to electricity in developing countries. This may be attributed to numerous factors, including affordability, inefficiency and lack of flexibility in electrification practices (Bouzarovski and Petrova 2015) (Khanna et al, 2015). In some cases, these may show non-intuitive effects. For instance, people in developing countries in the global south may be more vulnerable to climate induced heat stress become of large demand-supply gap in residential cooling (Mastrucci et al. 2019). The case of several African countries is notable in this paradigm. Even with projected ranges of development, Africa is projected to face energy poverty especially for household electricity use (Calvin et al. 2016). On one level, electrification in these countries may increase CO_2 emissions, which are contradictory to the Paris Agreement goals (Handayani et al. 2017; Dagnachew et al. 2018). However, there may be a considerable opportunity to rely upon both renewable energy and demand-side option to create a new framework of energy sector development (Yadav et al. 2019; Monyei and Adewumi 2017).

While electrification impacts on other SDGs is prominent based on some examples above, the literature has shown considerable focus on tradeoffs and synergies between energy and other SDGs (IPCC SR1.5, 2019; Denton et al, *in preparation*).

Broadly, the interlinkage with some of the themes is quite well understood, such as climate action. However, some of the more recent work conceptually identifies these interlinkages. In terms of identifying the linkages, “synergy” and “trade-offs” type definitions have been typically used not just in mapping this understanding (von Stechow et al. 2016) but also in several localized energy systems (Grubert and Webber 2015). Further, in some cases, scores have also been given to roughly gauge these interlinkages. Some of the critical questions that arise while answering these questions include (Fuso Nerini et al. 2018):

- Does the target require certain actions in relation to energy systems?
- Is there published evidence of synergies and trade-offs between the Target and decisions in pursuit of SDG7?
- How is this affected in the key evidence domains - Individual and collective aspirations of greater welfare and wellbeing, infrastructure for sustainable development and natural resources

Based on the coverage of various types of literature, some critical themes have been identified that include reduction in extreme events, human development benefits of electrification, desalination, fugitive emissions, waste-to-energy (McCollum et al. 2018c). As Figure 6.43 shows, the scope for positive interactions of energy systems with SDGs is considerably larger than the tradeoffs. Some examples to this effect include reduction in air pollution and water withdrawals from solar PV, improved scope of employment from BECCS and other examples given in section 6.4.4. Incidentally, several of these themes are either directly or indirectly incorporated within the IAM design as well (van Soest et al. 2019). Here, we discuss one specific theme (water-energy nexus) that has been particularly stressed by the literature. This is in extension of the air pollution-climate mitigation interaction covered in AR5 and Chapter 17 of this report.

Figure 6.43 Nature of the interactions between SDG7 (Energy) and the non-energy SDGs (McCollum et al. 2018c)**.**

The water impacts of decarbonizing the energy sector, especially in scenarios requiring large-scale negative emissions and CCS will be unprecedented. Various energy system models have begun to account for adaptation needs arising out of climate variability and water stress. This has been possible by coupling energy models with hydrological models given existing penetration of hydropower in the grid. These are in addition to the understanding of significant grid disruptions due to natural disasters – which are projected to be intensified in scale as well as frequency due to climate change (Feldpausch-

Parker et al. 2018). Some studies have indicated that water stress will cause critical reductions in reducing hydropower/thermoelectric power in the future (Zhou et al. 2019b; van Vliet et al. 2016). However, other studies also suggest that existing infrastructure may be more resilient than previously anticipated (Henry and Pratson 2016). Climate change induced water stress may also cause reduction in the summertime generation (thus increasing intra-annual variability), which is not accounted by generators currently (Bartos and Chester 2015). This calls for standby capacities or reserve margins (Miara et al. 2017), which will have inherent economic inefficiencies due to lower load factor dispatch. Despite regional differences, it is projected that response strategies would be robustly in the direction of cooling-system modifications (Cui et al. 2018).

Integrated studies are useful in understanding the overall water trends associated with the energy sector. However, it is also important to understand the prospects of reduction of water withdrawals from individual technologies such that effective attention may be paid to these areas. This is especially relevant because of several recent technological developments.

The first major energy shift – characterized by coal-to-gas switching – is the unconventional gas boom in the US that has been accompanied with increased produced water management needs (Bartholomew and Mauter 2016). This has catalyzed improved technology developments for large-scale desalination for non-RO treatable brines (Boo et al. 2016). This however causes reductions in overall energy efficiency since desalination has large energy requirements which has already affected the energy-for-water in the case of several countries (Liu et al. 2016). 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).

Most studies have pointed to the high water withdrawal rate of CO_2 capture technologies as the primary driver of increased water footprint, especially in scenarios with somewhat limited penetration of negative emission technologies. Suitable technological approaches have been suggested, such as utilizing hybrid cooling systems (Zhai and Rubin 2016; Lim-Wavde et al. 2018) and/or non-solvent based capture technologies will have reduced water impacts (Sharma and Mahapatra, 2018). Similarly, alternative configurations of CCS which utilizes bioenergy, relying on green-grey tradeoffs in consumptive water use may also be a potential avenue for abating freshwater stress (Beal et al. 2018). Overall, improvements in energy efficiency has been seen as a very potent way of reducing water implications in all the aforementioned studies, especially as improving structural efficiencies throughout sector may significantly reduce the need for large-scale NET adoption (Grubler et al. 2018).

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