accumulation. Recycling allows the reuse of nearly all - 83% in one study - of the components of PV modules, other than plastics (Ardente et al. 2019) and would add less than 1% to lifecycle GHG emissions (Latunussa et al. 2016). Glass accounts for 70% of the mass of a solar cell and is relatively easy to recycle. Recycling technology is advancing, but the scale and share of recycling is still small (Li et al. 2020d). By 2050, however, end-of-life PV could total 80 MT and comprise 10% of global electronic waste (Stolz and Frischknecht 2017), although most of it is glass. IEA runs a program to enable PV recycling by sharing best practices to minimise recycling life cycle impacts. Ensuring that a substantial amount of panels are recycled at end of life will likely require policy incentives, as the market value of the recovered materials, aside from aluminium and copper, is likely to be too low to justify recycling on its own (Deng et al. 2019). A near-term priority is maximizing the recovery of silver, silicon, and aluminium, the most valuable PV material components (Heath et al. 2020).

Many alternative PV materials are improving in efficiency and stability, providing longer-term pathways for continued PV costs reductions and better performance (*high confidence*). While solar PV based on semi-conductors constructed from wafers of silicon still captures 90% of the market, new designs and materials have the potential to reduce costs further, increase efficiency, reduce resource use, and open new applications. The most significant technological advance within silicon PV in the past ten years has been the widespread adoption of the passivated emitter and rear cell (PERC) design (Green 2015), which now accounts for the majority of production. This advance boosts efficiency over traditional aluminium backing by increasing reflectivity within the cell and reducing electron hole recombination (Blakers 2019). Bifacial modules increase efficiency by using reflected light from the ground or roof on the backside of modules (Guerrero-Lemus et al. 2016). Integrating PV into buildings can reduce overall costs and improve building energy performance (Shukla et al. 2016). Concentrating PV uses lenses or mirrors that collect and concentrate light onto high efficiency PV cells (Li et al. 2020a). Beyond crystalline silicon, thin films of amorphous silicon, cadmium telluride, and copper indium gallium selenide (among others) have the potential for much lower costs while their efficiencies have increased (Green et al. 2019). Perovskites, inexpensive and easy to produce crystalline structures, have increased in efficiency by a factor of six in the past decade; the biggest challenge is light-induced degradation as well as finding lead-free efficient compounds or establish lead recycling at the end of the life cycle of the device (Petrus et al. 2017; Chang et al. 2018; Wang et al. 2019b; Zhu et al. 2020). Organic solar cells are made of carbon-based semiconductors like the ones found in the displays made from organic light emitting diodes (OLEDs) and can be processed in thin films on large areas with scalable and fast coating processes on plastic substrates. The main challenges are raising the efficiency and improving their lifetime (Ma et al. 2020; Riede et al. 2021). Quantum dots, spherical semi-conductor nano-crystals, can be tuned to absorb specific wavelengths of sunlight giving them the potential for high efficiency with very little material use (Kramer et al. 2015). A common challenge for all emerging solar cell technologies is developing the corresponding production equipment. Hybrids of silicon with layers of quantum dots and perovskites have the potential to take advantage of the benefits of all three, although those designs require that these new technologies have stability and scale that match those of silicon (Palmstrom et al. 2019; Chang et al. 2017). This broad array of alternatives to making PV from crystalline silicon offer realistic potential for lower costs, reduced material use, and higher efficiencies in future years (Victoria et al. 2021).

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

Like PV, CSP facilities can deliver large amounts of power (up to 200 MW per unit) and maintain substantial thermal storage, which is valuable for load balancing over the diurnal cycle (McPherson et al. 2020). However, unlike PV, CSP can only use direct sunlight, constraining its cost-effectiveness to North Africa, the Middle East, Southern Africa, Australia, the Western U.S., parts of South America (Peru, Chile), the Western part of China, and Australia (Deng et al. 2015; Dupont et al. 2020). Parabolic troughs, central towers and parabolic dishes are the three leading solar thermal technologies (Wang et al. 2017d). Parabolic troughs represented approximately 70% of new capacity in 2018 with the balance made up by central tower plants (Islam et al. 2018). Especially promising research directions are on tower-based designs that can achieve high temperatures, useful for industrial heat and energy storage (Mehos et al. 2017), and direct steam generation designs (Islam et al. 2018). Costs of CSP have fallen by nearly half since AR5 (Figure 6.8) albeit at a slower rate than PV. Since AR5, almost all new CSP plants have storage (Figure 6.9)(Thonig 2020).

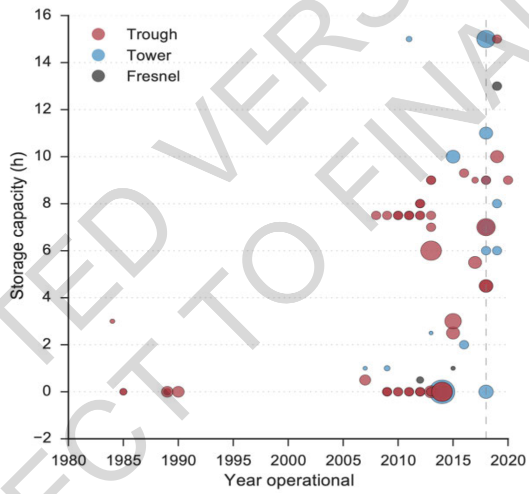


Figure 6.9 CSP plants by storage capacity in hours (vertical), year of installation (horizontal), and size of plant in MW (circle size). Since AR5, almost all new CSP plants have storage (Thonig 2020). Data source: https://csp.guru/metadata.html.

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

6.4.2.2 Wind Energy

Wind power is increasingly competitive with other forms of electricity generation and is the low-cost option in many applications (*high confidence*). Costs have declined by 18% and 40% on land and offshore since 2015 (*high confidence*), and further reductions can be expected by 2030 (*medium confidence*). Critical areas for continued improvement are technology advancements and economies of scale (*high confidence*). Global future potential is primarily limited by onshore land availability in wind power-rich areas, lack of supporting infrastructure, grid integration, and access to finance (especially in developing countries) (*high confidence*).

Energy from wind is abundant, and the estimated technical potentials surpass the total amount of energy needed to limit warming to well below 2°C (*high confidence*). Recent global estimates of potentially exploitable wind energy resource are in the range of 557–717 PWh yr^{-1} (2005–2580 EJ yr^{-1}) (Eurek et al. 2017; Bosch et al. 2017, 2018; McKenna et al. 2022), or 20–30 times the 2017 global electricity demand. Studies have suggested that ‘bottom-up’ approaches may overestimate technical potentials (Miller et al. 2015; Kleidon and Miller 2020). But even in the most conservative ‘top-down’ approaches, the technical wind potential surpasses the amount needed to limit warming to well below 2°C (Bosch et al. 2017; Eurek et al. 2017; Volker et al. 2017). The projected climate change mitigation from wind energy by 2100 ranges from 0.3°C–0.8°C depending on the precise socio-economic pathway and wind energy expansion scenario followed (Barthelmie and Pryor 2021). Wind resources are unevenly distributed over the globe and by time of the year (Petersen and Troen 2012), but potential hotspots exist on every continent (Figure 6.10) as expressed by the wind power density (a quantitative measure of wind energy available at any location). Technical potentials for onshore wind power vary considerably, often because of inconsistent assessments of suitability factors (McKenna et al. 2020). The potential for offshore wind power is larger than for onshore because offshore wind is stronger and less variable (Bosch et al. 2018). Offshore wind is more expensive, however, because of higher costs for construction, maintenance, and transmission. Wind power varies at a range of time scales, from annual to sub-seconds; the effects of local short-term variability can be offset by power plant control, flexible grid integration, and storage (Barra et al. 2021) (section 6.4.3). In some regions, interannual variations in wind energy resources could be important for optimal power system design (Wohland et al. 2019a; Coker et al. 2020).

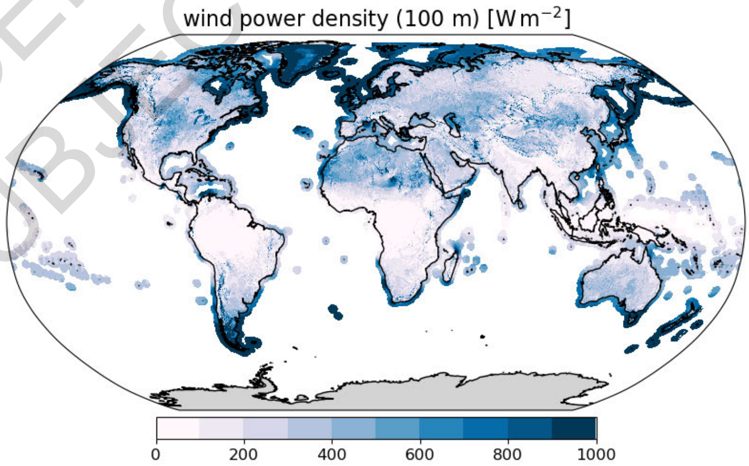


Figure 6.10 Mean wind power density [W m^{-2}] at 100 m above ground level over land and within 100 km of the coastline. Source: Global Wind Atlas https://globalwindatlas.info/

Wind power cost reductions (Figure 6.11) are driven mainly by larger capacity turbines, larger rotor diameters and taller hub heights - larger swept areas increase the energy captured and the capacity factors for a given wind speed; taller towers provide access to higher wind speeds (Beiter et al. 2021). All major onshore wind markets have experienced rapid growth in both rotor diameter (from 81.2 m in 2010 to 120 m in 2020) (IRENA 2021b), and average power ratings (from 1.9 MW in 2010 to 3 MW in 2020). The generation capacity of offshore wind turbines grew by a factor of 3.7 in less than two decades, from 1.6 MW in 2000 to 6 MW in 2020 (Wiser et al. 2021). Floating foundations could revolutionize offshore wind power by tapping into the abundant wind potential in deeper waters. This technology is particularly important for regions where coastal waters are too deep for fixed-bottom wind turbines. Floating wind farms potentially offer economic and environmental benefits compared with fixed-bottom designs due to less-invasive activity on the seabed during installation, but the long-term ecological effects are unknown and meteorological conditions further offshore and in deeper waters are harsher on wind turbine components (IRENA 2019c). A radical new class of wind energy converters has also been conceived under the name of Airborne Wind Energy Systems that can harvest strong, high-altitude winds (typically between 200–800m), which are inaccessible by traditional wind turbines (Cherubini et al. 2015). This technology has seen development and testing of small devices (Watson et al. 2019).

Wind capacity factors have increased over the last decade (Figure 6.11). The capacity factor for onshore wind farms increased from 27% in 2010 to 36% in 2020 (IRENA 2021a). The global average offshore capacity factor has decreased from a peak of 45% in 2017. This has been driven by the increased share of offshore development in China, where projects are often near-shore and use smaller wind turbines than in Europe (IRENA 2021b). Improvements in capacity factors also come from increased functionality of wind turbines and wind farms. 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, and therefore operate more efficiently and reach full capacity for a longer time period (Rohrig et al. 2019).

Electricity from onshore wind is less expensive than electricity generated from fossil fuels in a growing number of markets (*high confidence*). The global average LCOE onshore declined by 38% from 2010 to 2020 (Figure 6.11), reaching USD 0.039 kWh^{-1}. However, the decrease in cost varies substantially by region. Since 2014, wind costs have declined more rapidly than the majority of experts predicted (Wiser et al. 2021). New modelling projects onshore wind LCOE of USD .037 kWh^{-1} by 2030 (Junginger et al. 2020a), and additional reductions of 37–39% have been predicted by 2050 (Wiser et al. 2021). The future cost of offshore wind is more uncertain because other aspects besides increases in capacity factors influence the cost (Junginger et al. 2020b).

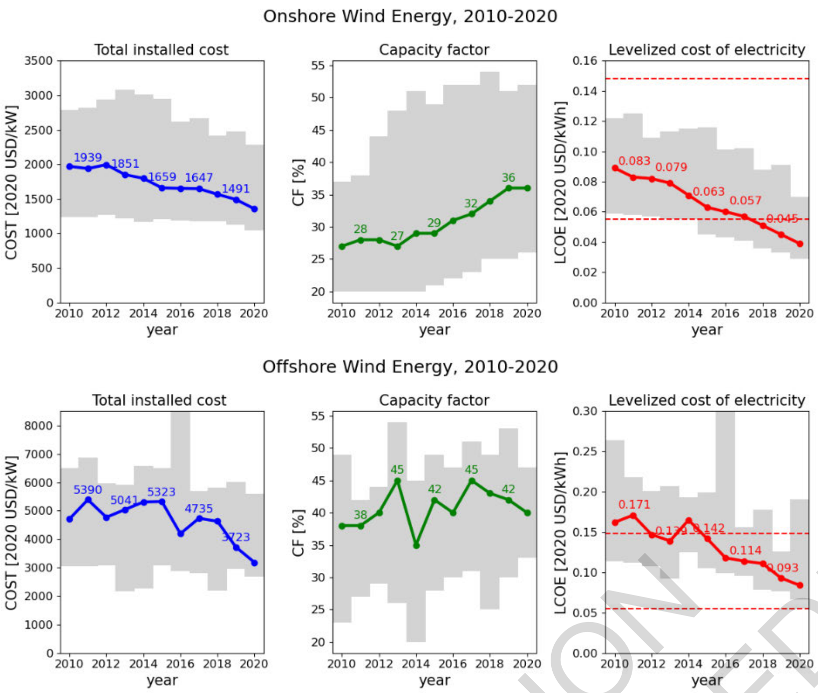


Figure 6.11 Global weighted average total installed costs, capacity factors, and LCOE for onshore (top) and offshore (bottom) wind power of existing power plants per year (2010-2020). The shaded area represents the 5th and 95th percentiles and the red dashed line represents the fossil fuel cost range. Source: (IRENA 2021a)

The cost of the turbine (including the towers) makes up the largest component of wind's LCOE. Total installed costs for both onshore and offshore wind farms have decreased since 2015 (Figure 6.11), but the total installed costs for onshore wind projects are very site- and market-specific, as reflected in the range of LCOEs. China, India, and the U.S. have experienced the largest declines in total installed costs. In 2020, typical country-average total installed costs were around USD 1150 kW^{-1} in China and India, and between USD 1403–2472 kW^{-1} elsewhere (IRENA 2021b). Total installed costs of offshore wind farms declined by 12% between 2010 and 2020. But, because some of the new offshore wind projects have moved to deeper waters and further offshore, there are considerable year-to-year variations in their price (IRENA 2021b). Projects outside China in recent years have typically been built in deeper waters (10–55 m) and up to 120 km offshore, compared to around 10 m in 2001–2006, when distances rarely exceeded 20 km. With the shift to deeper waters and sites further from ports, the total installed costs of offshore wind farms rose, from an average of around USD 2500 kW^{-1} in 2000 to around USD 5127 kW^{-1} by 2011–2014, before falling to around USD 3185 kW^{-1} in 2020 (IRENA 2020a). The full cost of wind power includes the transmission and system integration costs (Sections 6.4.3, 6.4.6. A new technology in development is the co-location of wind and solar PV power farms, also known as hybrid power plants. Co-locating wind, solar PV, and batteries can lead to synergies in electricity generation, infrastructure, and land usage, which may lower the overall plant cost compared to single technology systems (Lindberg et al. 2021).

Wind power plants pose relatively low environmental impact, but sometimes locally significant ecological effects (*high confidence*). The environmental impact of wind technologies, including CO_2 emissions, is concentrated in the manufacturing, transport, and building stage and in disposal as the end-of-life of wind turbines is reached (Liu and Barlow 2017; Mishnaevsky 2021). The operation of wind turbines produces no waste or pollutants. The LCA for wind turbines is strongly influenced by the operating lifetime, quality of wind resources, conversion efficiency, and size of the wind turbines

(Laurent et al. 2018; Kaldellis and Apostolou 2017). But, all wind power technologies repay their carbon footprint in less than a year (Bonou et al. 2016).

Wind farms can cause local ecological impacts, including impacts on animal habitat and movements, biological concerns, bird and 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 by selectively stopping some wind turbines in high risk locations, often without affecting the productivity of the wind farm (de Lucas et al. 2012). Many countries now require environmental studies of impacts of wind turbines on wildlife prior to project development, and, in some regions, shutdowns are required during active bird migration (de Lucas et al. 2012). Offshore wind farms can also impact migratory birds and other sea species (Hooper et al. 2017). Floating foundations pose lower environmental impacts at build stage (IRENA 2019c), but their cumulative long-term impacts are unclear (Goodale and Milman 2016). Recent studies find weak associations between wind farm noise and measures of long-term human health (Poulsen et al. 2018a,b, 2019a,b).

Public support for onshore and particularly offshore wind energy is generally high, although people may oppose specific wind farm projects (*high confidence*) (e.g., Rand and Hoen 2017; Steg 2018; Bell et al. 2005; Batel and Devine-Wright 2015). People generally believe that wind energy is associated with environmental benefits and that it is relatively cheap. Yet, some people believe wind turbines can cause noise and visual aesthetic pollution, threaten places of symbolic value (Russell et al. 2020; Devine-Wright and Wiersma 2020), and have adverse effects on wildlife (Bates and Firestone 2015), which challenges public acceptability (Rand and Hoen 2017). Support for local wind projects is higher when people believe fair decision-making procedures have been implemented (Aitken 2010a; Dietz and Stern 2008). Evidence is mixed whether distance from wind turbines or financial compensation increases public acceptability of wind turbines (Hoen et al. 2019; Rand and Hoen 2017; Cass et al. 2010; Rudolph et al. 2018). Offshore wind farms projects have higher public support, but can also face resistance (Rudolph et al. 2018; Bidwell 2017).

Common economic barriers to wind development are high initial cost of capital, long payback periods, and inadequate access to capital. Optimal wind energy expansion is most likely to occur in the presence of a political commitment to establish, maintain, and improve financial support instruments, technological efforts to support a local supply chains, and grid investments integrate VRE electricity (Diógenes et al. 2020).

[START BOX 6.4 HERE]

Box 6.4 Critical strategic minerals and a low-carbon energy system transition

The secure supply of many metals and minerals (e.g., cobalt, copper, lithium, and rare earth elements, REEs) is critical to supporting a low-emissions energy system transition (Sovacool et al. 2020). A low-carbon energy system transition will increase the demand for these minerals to be used in technologies like wind turbines, PV cells, and batteries (World Bank 2020). Reliance on these minerals has raised questions about possible constraints to a low-carbon energy system transition, including supply chain disruptions (Chapter 10.6). Concerns have also been raised about mining for these materials, which frequently results in severe environmental impacts (Sonter et al. 2020), and metal production itself is energy-intensive and difficult to decarbonize (Sovacool et al. 2020).

Wind energy depends on two critical REEs - neodymium and dysprosium - used in magnets in high-performance generators (Pavel et al. 2017; Li et al. 2020b). Silicon-wafer-based solar PV, which accounted for 95% of PV production in 2020, does not use REEs but utilizes aluminium, copper, and silver (IEA 2021a). Lithium, nickel, cobalt, and phosphorous are used in batteries. Many critical minerals are used in EVs, including aluminium and copper in manufacturing the necessary EV charging infrastructure, and neodymium in permanent magnet motors.

These strategic minerals are found in a limited number of countries, and concerns have been raised that geopolitical factors could disrupt the supply chain necessary for a low-carbon energy system transition. However, excluding cobalt and lithium, no single country holds more than a third of the world reserves. The known supply of some strategic minerals is still close to 600 years at current levels of demand (BP 2020), but increased demand would cut more quickly into supplies.

There are alternatives to the strategic minerals currently used to support a low-carbon transition. Wind turbines can be manufactured without permanent magnets to reduce the need for strategic minerals, but the production costs are higher, and their efficiency is reduced (Månberger and Stenqvist 2018). Alternatives to silicon, such as thin films, could be used to produce PVs. Thin-films use much less material than silicon-based PV, but they contain other potentially critical metals like tellurium, cadmium, and gallium. Alternatives to lithium-ion batteries, such as sodium-ion batteries, are becoming more practical and feasible (Sovacool et al. 2020).

[END BOX 6.4HERE]

6.4.2.3 Hydroelectric Power

Hydropower is technically mature, proved worldwide as a primary source of renewable electricity, and may be used to balance electricity supply by providing flexibility and storage. The LCOE of hydropower is lower than the cheapest new fossil fuel-fired option. However, the future mitigation potential of hydropower depends on minimizing environmental and social impacts during the planning stages, reducing the risks of dam failures, and modernising the aging hydropower fleet to increase generation capacity and flexibility (*high confidence*).

Estimates of global gross theoretical available hydropower potential varies from 31–128 PWh yr^{-1} (112–460 EJ yr^{-1}), exceeding total electricity production in 2018 (Banerjee et al. 2017; IEA 2021d; BP 2020). This potential is distributed over 11.8 million locations (Figure 6.12), but many of the locations cannot be developed for (current) technical, economic, or political reasons. The estimated technical potential of hydropower is 8–30 PWh yr^{-1} (29–108 EJ yr^{-1}), and its estimated economic potential is 8–15 PWh yr^{-1} (29–54 EJ yr^{-1}) (van Vliet et al. 2016c; Zhou et al. 2015). Actual hydropower generation in 2019 was 4.2 PWh (15.3 EJ), providing about 16% of global electricity and 43% of global electricity from renewables (BP 2020; Killingtveit 2020; IEA 2020f). Asia holds the largest hydropower potential (48%), followed by S. America (19%) (Hoes et al. 2017).

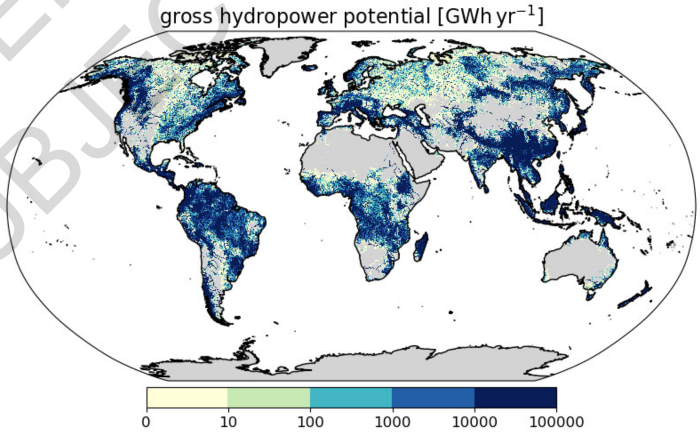


Figure 6.12 Global map of gross hydropower potential distribution [GWh yr^{-1}], Data: (Hoes et al. 2017)

Hydropower is a mature technology with locally adapted solutions (*high confidence*) (Zhou et al. 2015; Killingtveit 2020). The peak efficiency of hydroelectric plants is greater than 85%. Hydropower plants without storage or with small storage typically produce a few kWs to 10 MWs (examples of such plants producing higher amounts do exist), and are useful for providing electricity at a scale from households to small communities (El Bassam et al. 2013; Towler 2014). However, hydropower plants without or with small storage may be susceptible to climate variability, especially droughts, when the amount of water may not be sufficient to generate electricity (see Section 6.5, Premalatha et al. 2014).

Hydropower plants with storage may produce 10 GW, reaching over 100 TWh yr^{-1} (0.36 EJ yr^{-1}), but generally require large areas. Pumped storage hydropower stores energy by pumping water to higher reservoirs during low-demand periods (Killingtveit 2020). The storage in hydropower systems provides flexibility to compensate for rapid variations in electricity loads and supplies. The regulating characteristics of the storage play an important role in assuring continuity of energy supply from renewable sources (Yang et al. 2018b).

Hydropower is one of the lowest-cost electricity technologies (Mukheibir 2013; IRENA 2021b). Its operation and maintenance costs are typically 2–2.5% of the investment costs per kW yr^{-1} for a lifetime of 40–80 years (Killingtveit 2020). Construction costs are site specific. The total cost for an installed large hydropower project varies from USD 10,600–804,500 kW^{-1} if the site is located far away from transmission lines, roads, and infrastructure. Investment costs increase for small hydropower plants and may be as high as USD 100,000 kW^{-1} or more for the installation of plants of less than 1 MW - 20% to 80% more than for large hydropower plants (IRENA 2015). During the past 100 years, total installed costs and LCOE have risen by a few percent, but the LCOE of hydropower remains lower than the cheapest new fossil fuel-fired option (IRENA 2019b, 2021).

Hydroelectric power plants may pose serious environmental and societal impacts (*high confidence*) (Mccartney 2009). Dams may lead to fragmentation of ecological habitats because they act as barriers for migration of fish and other land and water-borne fauna, sediments, and water flow. These barriers can be mitigated by sediment passes and fish migration aids, and with provision of environmental flows. Below dams, there can be considerable alterations to vegetation, natural river flows, retention of sediments and nutrients, and water quality and temperature. Construction of large reservoirs leads to loss of land, which may result in social and environmental consequences. Minimizing societal and environmental impacts requires taking into account local physical, environmental, climatological, social, economic, and political aspects during the planning stage (Killingtveit 2020). Moreover, when large areas of land are flooded by dam construction, they generate GHGs (Phyoe and Wang 2019; Maavara et al. 2020; Prairie et al. 2018). On the other hand, hydropower provides flexible, competitive low-emission electricity, local economic benefits (e.g., by increasing irrigation and electricity production in developing countries), and ancillary services such as municipal water supply, irrigation and drought management, navigation and recreation, and flood control (IRENA 2021b). However, the long term economic benefits to communities affected by reservoirs are a subject of debate (de Faria et al. 2017; Catolico et al. 2021).

Public support for hydroelectric energy is generally high (Steg 2018), and higher than support for coal, gas, and nuclear. Yet, public support for hydro seems to differ for existing and new projects (*high confidence*). Public support is generally high for small and medium scale hydropower in regions where hydropower was historically used (Gormally et al. 2014). Additionally, there is high support for existing large hydropower projects in Switzerland (Plum et al. 2019; Rudolf et al. 2014), Canada (Boyd et al. 2019), and Norway (Karlstrøm and Ryghaug 2014), where it is a trusted and common energy source. Public support seems lower for new hydropower projects (Hazboun and Boudet 2020), and the construction of new large hydropower plants has been met with strong resistance in some areas (Bronfman et al., 2015; Vince, 2010). People generally perceive hydroelectric energy as clean and a non-contributor to climate change and environmental pollution (Kaldellis et al. 2013). For example, in Sweden, people believed that existing hydropower projects have as few negative environmental impacts as solar, and even less than wind (Ek 2005). However, in areas where the construction of new large-scale hydroelectric energy is met with resistance, people believe that electricity generation from hydro can cause environmental, social, and personal risks (Bronfman et al., 2012; Kaldellis et al., 2013).

The construction time of hydroelectric power plants is longer than many other renewable technologies, and that construction time may be extended by the additional time it takes to fill the reservoir. This extended timeline can create uncertainty in the completion of the project. The uncertainty is due to insecurity in year-to-year variations in precipitation and the water inflows required to fill reservoirs. This is especially critical in the case of trans-boundary hydroelectric power plants, where filling up the reservoirs can have large implications on downstream users in other nations. As a result of social and environmental constraints, only a small fraction of potential economic hydropower projects can be developed, especially in developed countries. Many developing countries have major undeveloped hydropower potential, and there are opportunities to develop hydropower combined with other economic activities such as irrigation (Lacombe et al. 2014). Competition for hydropower across country borders can lead to conflict, which could be exacerbated if climate alters rainfall and streamflow (Ito et al. 2016).

6.4.2.4 Nuclear Energy

Nuclear power can deliver low-carbon energy at scale (*high confidence*). Doing so will require improvements in managing construction of reactor designs that hold the promise of lower costs and broader use (*medium confidence*). At the same time, nuclear power continues to be affected by cost overruns, high up-front investment needs, challenges with final disposal of radioactive waste, and varying public acceptance and political support levels (*high confidence*).

There are sufficient resources for substantially increasing nuclear deployment (*medium confidence*). Estimates for identified uranium resources have been increasing steadily over the years. Conventional uranium resources have been estimated to be sufficient for over 130 years of supply at current levels of use; 100 years were estimated in 2009 (Hahn 1983; NEA/IAEA 2021). In the case of future uranium resource scarcity, thorium or recycling of spent fuel might be used as alternatives. Interest in these alternatives has waned with better understanding of uranium deposits, their availability, and low prices (OECD NEA 2015; IAEA 2005).

There are several possible nuclear technology options for the period from 2030 to 2050 (*medium confidence*). In addition to electricity, nuclear can also be used to produce low-carbon hydrogen and freshwater (Kayfeci et al. 2019; Kavvadias and Khamis 2014)

- **Large reactors**. The nuclear industry has entered a new phase of reactor construction, based on evolutionary designs. These reactors achieve improvements over previous designs through small to moderate modifications, including improved redundancy, increased application of passive safety features, and significant improvements to containment design to reduce the risk of a major accident (MIT 2018). Examples include European - EPR, Korean - APR1400, U.S. - AP1000, Chinese - HPR1000 or Russian - VVER-1200.
- **Long-term operation (LTO) of the current fleet**. Continued production from nuclear power will depend in part on life extensions of the existing fleet. By the end of 2020, two-thirds of nuclear power reactors will have been operational for over 30 years. The design lifetime of most of existing reactors is 30–40 years. Engineering assessments have established that reactors can operate safely for longer if key replaceable components (e.g., steam generator, mechanical and electrical equipment, instrumentation and control parts) are changed or refurbished (IAEA 2018). The first lifetime extension considered in most of the countries typically is 10–20 years (OECD IEA NEA 2020).
- **Small Modular Reactors**. There are more than 70 SMR designs at different stages of consideration and development, from the conceptual phase to licensing and construction of first-of-a-kind facilities (IAEA 2020). Due to smaller unit sizes, the SMRs are expected to have lower total investment costs, although the cost per unit of generation might be higher than conventional large reactors (Mignacca and Locatelli 2020). Modularity and off-site pre-production may allow greater efficiency in construction, shorter delivery times, and overall cost optimization (IEA 2019c). SMR

designs aim to offer an increased load-following capability that makes them suitable to operate in smaller systems and in systems with increasing shares of VRE sources. Their market development by the early 2030s will strongly depend on the successful deployment of prototypes during the 2020s.

Nuclear power costs vary substantially across countries (*high confidence*). First-of-a-kind projects under construction in Northern America and Europe have been marked by delays and costs overruns (Berthelemy and Rangel 2015). Construction times have exceeded 13–15 years and cost has surpassed 3–4 times initial budget estimates (OECD IEA NEA 2020). In contrast, most of the recent projects in Eastern Asia (with construction starts from 2012) were implemented within 5–6 years (IAEA PRIS 2021). In addition to region-specific factors, future nuclear costs will depend on the ability to benefit from the accumulated experience in controlling the main drivers of cost. These cost drivers fall into four categories: design maturity, project management, regulatory stability and predictability, and multi-unit and series effects (NEA 2020). With lessons learned from first-of-a-kind projects, the cost of electricity for new builds are expected to be in the range of USD 42–102 MWh^{-1} depending on the region (OECD IEA NEA 2020).

Lifetime extensions are significantly cheaper than new builds and cost competitive with other low-carbon technologies. The overnight cost of lifetime extensions is estimated in the range of USD 390–630 kWe^{-1} for Europe and North America, and the LCOE in the range of USD 30–36 MWh^{-1} for extensions of 10–20 years (OECD IEA NEA 2020).

Cost-cutting opportunities, such as design standardization and innovations in construction approaches, are expected to make SMRs competitive against large reactors by 2040 (Rubio and Tricot 2016) (*medium confidence*). As SMRs are under development, there is substantial uncertainty regarding the construction costs. Vendors have estimated first-of-a-kind LCOEs at USD 131–190 MWh^{-1}. Effects of learning for nth-of-a-kind SMR are anticipated to reduce the first-of-a-kind LCOE by 19–32%.

Despite low probabilities, the potential for major nuclear accidents exists, and the radiation exposure impacts could be large and long-lasting (Steinhauser et al. 2014). However, new reactor designs with passive and enhanced safety systems reduce the risk of such accidents significantly (*high confidence*). The (normal) activity of a nuclear reactor results in low volumes of radioactive waste, which requires strictly controlled and regulated disposal. On a global scale, roughly 421 ktons of spent nuclear fuel have been produced since 1971 (IEA 2014). Out of this volume, 2–3% is high-level radioactive waste, which presents challenges in terms of radiotoxicity and decay longevity, and ultimately entails permanent disposal.

Nuclear energy is found to be favourable regarding land occupation (Cheng and Hammond 2017; Luderer et al. 2019) and ecological impacts (Brook and Bradshaw 2015; Gibon et al. 2017). Similarly, bulk material requirements per unit of energy produced are low (e.g. aluminum, copper, iron, rare earth metals) (Vidal et al. 2013; Luderer et al. 2019). Water-intensive inland nuclear power plants may contribute to localized water stress and competition for water uses. The choice of cooling systems (closed-loop instead of once-through) can significantly moderate withdrawal rates of the freshwater (Jin et al. 2019; Fricko et al. 2016; Mouratiadou et al. 2016; Meldrum et al. 2013). Reactors situated on the seashore are not affected by water scarcity issues (JRC EU 2021). Life cycle assessment (LCA) studies suggest that the overall impacts on human health (in terms of disability adjusted life years (DALYs) from the normal operation of nuclear power plants are substantially lower than those caused by fossil fuel technologies and are comparable to renewable energy sources (Treyer et al. 2014; Gibon et al. 2017).

Nuclear power continues to suffer from limited public and political support in some countries (*high confidence*). Public support for nuclear energy is consistently lower than for renewable energy and natural gas, and in many countries as low as support for energy from coal and oil (Hobman and

Ashworth 2013; Corner et al. 2011; Pampel 2011). The major nuclear accidents (i.e. Three Mile Island, Chernobyl, and Fukushima) decreased public support (Poortinga et al. 2013; Bird et al. 2014). The public remains concerned about the safety risks of nuclear power plants and radioactive materials (Tsujikawa et al. 2016; Bird et al. 2014; Pampel 2011). At the same time, some groups see nuclear energy as a reliable energy source, beneficial for the economy and helpful in climate change mitigation. Public support for nuclear energy is higher when people are concerned about energy security, including concerns about the availability of energy and high energy prices (Gupta et al. 2019b; Groot et al. 2013), and when they expect local benefit (Wang et al. 2020c). Public support also increases when trust in managing bodies is higher (de Groot and Steg 2011). Similarly, transparent and participative decision-making processes enhance perceived procedural fairness and public support (Sjoberg 2004).

Because of the sheer scale of the investment required (individual projects can exceed USD 10 billion in value), nearly 90% of nuclear power plants under construction are run by state-owned or controlled companies with governments assuming significant part of the risks and costs. For countries that choose nuclear power in their energy portfolio, stable political conditions and support, clear regulatory regimes, and adequate financial framework are crucial for successful and efficient implementation.

Many countries have adopted technology-specific policies for low-carbon energy courses, and these policies influence the competitiveness of nuclear power. For example, feed-in-tariffs and feed-in premiums for renewables widely applied in the EU (Kitzing et al. 2012) or renewable portfolio standards in the U.S. (Barbose et al. 2016) impact wholesale electricity price (leading occasionally to low or even negative prices), which affects the revenues of existing nuclear and other plants (Bruninx et al. 2013; Newbery et al. 2018; Lesser 2019).

Nuclear power's long-term viability may hinge on demonstrating to the public and investors that there is a long-term solution to spent nuclear fuel. Evidence from countries steadily progressing towards first final disposals - Finland, Sweden and France - suggests that broad political support, coherent nuclear waste policies, and a well-managed, consensus-based decision-making process are critical for accelerating this process (Metlay 2016). Proliferation concerns surrounding nuclear power are related to fuel cycle (i.e., uranium enrichment and spent fuel processing). These processes are implemented in a very limited number of countries following strict national and internationals norms and rules, such as IAEA guidelines, treaties, and conventions. Most of the countries which might introduce nuclear power in the future for their climate change mitigation benefits do not envision developing their own full fuel cycle, significantly reducing any risks that might be linked to proliferation (IAEA 2014, 2019).

6.4.2.5 Carbon Dioxide Capture, Utilization, and Storage

Since AR5, there have been increased efforts to develop novel platforms that reduce the energy penalty associated with CO_2 capture, develop CO_2 utilization pathways as a substitute to geologic storage, and establish global policies to support CCS (*high confidence*). CCS can be used within electricity and other sectors. While it increases the costs of electricity, CCS has the potential to contribute significantly to low-carbon energy system transitions (IPCC 2018).

The theoretical global geologic storage potential is about 10,000 Gt-CO_2, with more than 80% of this capacity existing in saline aquifers (*medium confidence*). Not all the storage capacity is usable because geologic and engineering factors limit the actual storage capacity to an order of magnitude below the theoretical potential, which is still more than the CO_2 storage requirement through 2100 to limit temperature change to 1.5°C (Martin-Roberts et al. 2021) (*high confidence*). One of the key limiting factors associated with geologic CO_2 storage is the global distribution of storage capacity (Table 6.2). Most of the available storage capacity exists in saline aquifers. Capacity in oil and gas reservoirs and coalbed methane fields is limited. Storage potential in the U.S. alone is >1,000 Gt-CO_2, which is more than 10% of the world total (NETL 2015). The Middle East has more than 50% of global enhanced oil recovery potential (Selosse and Ricci 2017). It is likely that oil and gas reservoirs will be developed before saline aquifers because of existing infrastructure and extensive subsurface data (Alcalde et al. 2019; Hastings and Smith 2020). Notably, not all geologic storage is utilizable. In places with limited geologic storage, international CCS chains are being considered, where sources and sinks of CO_2 are located in two or more countries (Sharma and Xu 2021). For economic long-term storage, the desirable conditions are a depth of 800-3000 m, thickness of greater than 50 m and permeability greater than 500 mD (Singh et al. 2020; Chadwick et al. 2008). Even in reservoirs with large storage potential, the rate of injection might be limited by the subsurface pressure of the reservoir (Baik et al. 2018a). It is estimated that geologic sequestration is safe with overall leakage rates at <0.001% yr^{-1} (Alcalde et al. 2018). In many cases, geological storage resources are not located close to CO_2 sources, increasing costs and reduces viability (Garg et al. 2017a).

Table 6.2 Geologic storage potential across underground formations globally. These represent order-of-magnitude estimates. Data: (Selosse and Ricci 2017)

Reservoir Type	Africa	Australia	Canada	China	CSA	EEU	FSU	India	MEA	Mexico	ODA	USA	WEU
Enhanced Oil Recovery	3	0	3	1	8	2	15	0	38	0	1	8	0
Depleted oil and gas fields	20	8	19	1	33	2	191	0	252	22	47	32	37
Enhanced Coalbed Methane Recovery	8	30	16	16	0	2	26	8	0	0	24	90	12
Deep saline aquifers	1000	500	667	500	1000	250	1000	500	500	250	1015	1000	250

CSA: Central and South America, EEU: Eastern Europe, FSU: Former Soviet Union, MEA: Middle East, ODA: Other Asia (except China and India), WEU: Western Europe.

CO_2 utilization (CCU) - instead of geologic storage - could present an alternative method of decarbonization (*high confidence*). The global CO_2 utilization potential, however, is currently limited to 1–2 $GtCO_2$ yr^{-1} for use of CO_2 as a feedstock (Hepburn et al. 2019; Kätelhön et al. 2019) but could increase to 20 $GtCO_2$ by the mid-century (*medium confidence*). CCU involves using CO_2 as a feedstock to synthesize products of economic value and as substitute to fossil feedstock. However, several CO_2 utilization avenues might be limited by energy availability. Depending on the utilization pathway, the CO_2 may be considered sequestered for centuries (e.g., cement curing, aggregates), decades (plastics), or only a few days or months (e.g. fuels) (Hepburn et al. 2019). Moreover, when carbon-rich fuel end-products are combusted, CO_2 is emitted back into the atmosphere. Because of presence of several industrial clusters (regions with high density of industrial infrastructure) globally, a number of regions demonstrate locations where CO_2 utilization potential could be matched with large point sources of CO_2 (Wei et al. 2020).

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

Existing post-combustion approaches relying on absorption are technologically ready for full-scale deployment (*high confidence*). More novel approaches using membranes and chemical looping that might reduce the energy penalty associated with absorption are in different stages of development - ranging from laboratory phase to prototype phase (Abanades et al. 2015) (*high confidence*). There has been significant progress in post-combustion capture technologies that used absorption in solvents such as monoethanol amine (MEA). There are commercial-scale application of solvent-based absorption at two facilities – Boundary Dam since 2015 and Petra Nova (temporarily suspended) since 2017, with capacities of 1 and 1.6 $MtCO_2$ yr^{-1} respectively (Mantripragada et al. 2019; Giannaris et al. 2020a).

Several 2nd and 3rd generation capture technologies are being developed with the aim of not just lowering costs but also enhancing other performance characteristics such as improved ramp-up and lower water consumption. These include processes such as chemical looping, which also has the advantage of being capable of co-firing with biomass (Bhave et al. 2017; Yang et al. 2019). Another important technological development is the Allam cycle, which utilizes CO_2 as a working fluid and operates based on oxy-combustion capture. Applications using the Allam Cycle can deliver net energy efficiency greater than 50% and 100% CO_2 capture, but they are quite sensitive to oxygen and CO_2 purity needs (Scaccabarozzi et al. 2016; Ferrari et al. 2017).

CO_2 capture costs present a key challenge, remaining higher than USD 50 tCO_2^{-1} for most technologies and regions; novel technologies could help reduce some costs (*high confidence*). The capital cost of a coal or gas electricity generation facility with CCS is almost double one without CCS (Zhai and Rubin 2016; Rubin et al. 2015; Bui et al. 2018). Additionally, the energy penalty increases the fuel requirement for electricity generation by 13–44%, leading to further cost increases (Table 6.3).

Table 6.3 Costs and efficiency parameters of CCS in electric power plants. Data: (Muratori et al. 2017a)

	Capital Cost [USD kW^{-1}]	Efficiency [%]	CO_2 Capture Cost [USD ton-CO_2^{-1}]	CO_2 Avoided Cost [USD ton-CO_2^{-1}]
Coal (steam plant) + CCS	5800	28%	63	88
Coal (IGCC) + CCS	6600	32%	61	106
Natural Gas (CC) + CCS	2100	42%	91	33
Oil (CC) + CCS	2600	39%	105	95
Biomass (steam plant) + CCS	7700	18%	72	244
Biomass (IGCC) + CCS	8850	25%	66	242

In addition to reductions in capture costs, other approaches to reduce CCS costs rely on utilizing the revenues from co-products such as oil, gas, or methanol, and on clustering of large-point sources to reduce infrastructure costs. The potential for such reductions is limited in several regions due to low sink availability, but it could jumpstart initial investments (*medium confidence*). Injecting CO_2 into hydrocarbon formations for enhanced oil or gas recovery can produce revenues and lower costs (Edwards and Celia 2018). While enhanced oil recovery potential is <5% of the actual CCS needs, they can enable early pilot and demonstration projects (Núñez-López and Moskal 2019; Núñez-López et al. 2019). Substantial portions of CO_2 are effectively stored during enhanced oil recovery (Sminchak et al. 2020; Menefee and Ellis 2020). By clustering together of several CO_2 sources, overall costs may be reduced by USD 10 tCO_2^{-1} (Abotalib et al. 2016; Garg et al. 2017a), but geographical circumstances determine the prospects of these cost reductions via economies-of-scale. The major pathways for methanol, methane, liquid fuel production, and cement curing have costs greater than USD 500 tCO_2^{-1} (Hepburn et al. 2019). The success of these pathways therefore depends on the value of such fuels and on the values of other alternatives.

The public is largely unfamiliar with carbon capture, utilization, and storage technologies (Tcvetkov et al. 2019; L'Orange Seigo et al. 2014) (*high confidence*), and many people may not have formed stable attitudes and risk perceptions regarding these technologies (Daamen et al. 2006; Jones et al. 2015; Van Heek et al. 2017) *(medium confidence)*. In general, low support has been reported for CCS technologies (Allen and Chatterton 2013; Demski et al. 2017). When presented with neutral information on CCS, people favour other mitigation options such as renewable energy and energy efficiency (de Best-Waldhober et al. 2009; Scheer et al. 2013; Karlstrøm and Ryghaug 2014). Although few totally reject CCS, specific CCS projects have faced strong local resistance, which has contributed to the cancellation of CCS projects (Terwel et al. 2012; L'Orange Seigo et al. 2014). Communities may also consider CCU to be lower-risk and view it more favourably than CCS (Arning et al. 2019).

CCS requires considerable increases in some resources and chemicals, most notably water. Power plants with CCS could shutdown periodically due to water scarcity. In several cases, water withdrawals for CCS are 25–200% higher than plants without CCS (Yang et al. 2020; Rosa et al. 2020b) due to energy penalty and cooling duty. The increase is slightly lower for non-absorption technologies. In regions prone to water scarcity such as the Southwestern U.S. or Southeast Asia, this may limit deployment and result in power plant shutdowns during summer months (Liu et al. 2019b; Wang et al. 2019c). The water use could be managed by changing heat integration strategies and implementing reuse of wastewater (Magneschi et al. 2017; Giannaris et al. 2020b).

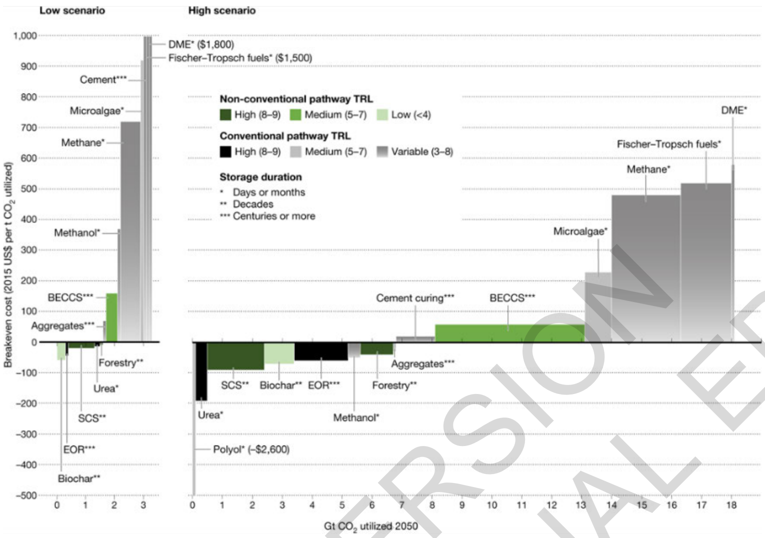


Figure 6.13 Costs and potential for different CO_2 utilization pathways (Hepburn et al. 2019)

Because CCS always adds cost, policy instruments are required for it to be widely deployed (*high confidence*). Relevant policy instruments include financial instruments such as emission certification and trading, legally enforced emission restraints, and carbon pricing (Haszeldine 2016; Kang et al. 2020). There are some recent examples of policy instruments specifically focused on promoting CCS. The recent U.S. 45Q tax credits offers nationwide tax credits for CO_2 capture projects above USD 35–50 tCO_2^{-1} which offset CO_2 capture costs at some efficient plants (Esposito et al. 2019). Similarly, California's low-carbon fuel standard offers benefits for CO_2 capture at some industrial facilities such as biorefineries and refineries (Von Wald et al. 2020).

6.4.2.6 Bioenergy

Bioenergy has the potential to be a high-value and large-scale mitigation option to support many different parts of the energy system. Bioenergy could be particularly valuable for sectors with limited alternatives to fossil fuels (e.g., aviation, heavy industry), production of chemicals and products, and, potentially, in carbon dioxide removal (CDR) via BECCS or biochar. While traditional biomass and first-generation biofuels are widely used today, the technology for large-scale production from advanced processes is not competitive, and growing dedicated bioenergy crops raises a broad set of sustainability concerns. Its long-term role in low-carbon energy systems is therefore uncertain (*high confidence*). [Note that this section focuses on the key technological developments for deployment of commercial bioenergy.]

Bioenergy is versatile: technology pathways exist to produce multiple energy carriers from biomass - electricity, liquid fuels, gaseous fuels, hydrogen, and solid fuels - as well as other value-added products *(high confidence)*. Different chemical and biological conversion pathways exist to convert diverse biomass feedstocks into multiple final energy carriers (Figure 6.14). Currently, biomass is mostly used to produce heat or for cooking purposes (traditional biomass), electricity, or first-generation sugar-based biofuels (e.g., ethanol produced via fermentation), as well as biodiesel produced from vegetable oils and animal fats. Electricity generated from biomass contributes about 3% of global generation. Tens of billions of gallons of first-generation biofuels are produced per year. The processing requirements (drying, dewatering, pelletizing) of different feedstocks for producing electricity from biomass are energy-intensive, and when utilizing current power plants, the efficiency is around 22%, with an increase up to 28% with advanced technologies (Zhang et al. 2020).

Scaling up bioenergy use will require advanced technologies such as gasification, Fischer-Tropsch processing, hydrothermal liquefaction (HTL), and pyrolysis. These pathways could deliver several final energy carriers starting from multiple feedstocks, including forest biomass, dedicated cellulosic feedstocks, crop residues, and wastes (Figure 6.14). While potentially cost-competitive in the future, pyrolysis, Fischer-Tropsch, and HTL are not currently cost-competitive (IEA 2018c; Molino et al. 2018; Prussi et al. 2019), and scaling-up these processes will require robust business strategies and optimized use of co-products (Lee and Lavoie 2013). Advanced biofuels production processes are at the pilot or demonstration stage and will require substantial breakthroughs or market changes to become competitive. Moreover, fuels produced from these processes require upgrading to reach “drop-in” conditions – that is, conditions in which they may be used directly consistent with current standards in existing technologies (van Dyk et al. 2019). Additional opportunities exist to co-optimize second generation biofuels and engines (Ostadi et al. 2019; Salman et al. 2020). In addition, gaseous wastes, or high-moisture biomass, such as dairy manure, wastewater sludge and organic MSW could be utilized to produce renewable natural gas. Technologies for producing biogas (e.g. digestion) tend to be less efficient than thermochemical approaches and often produce large amounts of CO_2, requiring the produced fuels to undergo significant upgrading (Melara et al. 2020).

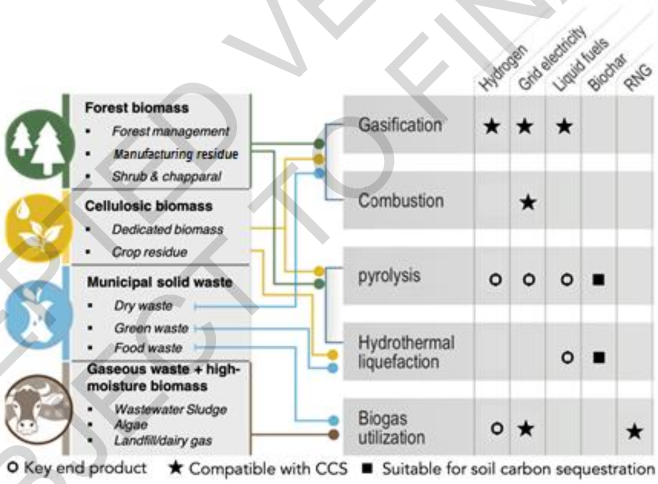


Figure 6.14 Range of advanced bioenergy conversion pathways (excluding traditional biomass, direct heat generation, first-generation biofuels, and non-energy products) based on feedstock, targeted end product, and compatibility with CDR via CCS and soil carbon sequestration (Modified from Baker et al, 2020)

A major scale-up of bioenergy production will require dedicated production of advanced biofuels. First generation biofuels produced directly from food crops or animal fats both have limited potential and lower yield per land area than advanced biofuels. Wastes and residues (e.g., from agricultural, forestry, animal manure processing) or biomass grown on degraded, surplus, and marginal land can provide opportunities for cost-effective and sustainable bioenergy at significant but limited scale (Saha and Eckelman 2018; Fajardy and Mac Dowell 2020; Spagnolo et al. 2020; Morris et al. 2013). Assessing the potential for a major scale-up of purpose-grown bioenergy is challenging due to its far-reaching linkages to issues beyond the energy sector, including competition with land for food production and forestry, water use, impacts on ecosystems, and land-use change) (IPCC 2020; Chapter 12; (Roe et al. 2021)). These factors, rather than geophysical characteristics, largely define the potential for bioenergy and explain the difference in estimates of potential in the literature. Biomass resources are not always in close proximity to energy demand, necessitating additional infrastructure or means to transport biomass or final bioenergy over larger distances and incur additional energy use (Baik et al. 2018b; Singh et al. 2020).

An important feature of bioenergy is that it can be used to remove carbon from the atmosphere by capturing CO_2 in different parts of the conversion process and then permanently storing the CO2 (BECCS or biochar) (Chapter 3, Chapter 7; Chapter 12.5; Smith et al. 2016; Fuss et al. 2018). Some early opportunities for low-cost BECCS are being utilized in the ethanol sector but these are applicable only in the near-term at the scale of $\leq$100 Mt-CO_2 yr^{-1} (Sanchez et al. 2018). Several technological and institutional barriers exist for large-scale BECCS implementation, including large energy requirements for CCS, limit and cost of biomass supply and geologic sinks for CO_2 in several regions, and cost of CO_2 capture technologies (*high confidence*). Besides BECCS, biofuels production through pyrolysis and hydrothermal liquefaction creates biochar, which could also be used to store carbon as 80% of the carbon sequestered in biochar will remain in the biochar permanently (Chapter 7). In addition to its ability to sequester carbon, biochar can be used as a soil amendment (Wang et al. 2014b).

First-generation bioenergy is currently competitive in some markets, though on average its costs are higher than other forms of final energy. Bioenergy from waste and residues from forestry and agriculture is also currently competitive, but the supply is limited (Aguilar et al. 2020). These costs are context-dependent, and regions having large waste resources are already producing low-cost bioenergy (Jin and Sutherland 2018). In the future, technology costs are anticipated to decrease, but bioenergy produced through cellulosic feedstocks may remain more expensive than fossil alternatives. Large-scale deployment of early opportunities especially in the liquid fuel sector may reduce the technological costs associated with biomass conversion (IEA 2020g). At the same time, the cost of feedstocks may rise as bioenergy requirements increase, especially in scenarios with large bioenergy deployment (Muratori et al. 2020). The costs of bioenergy production pathways are highly uncertain (Table 6.4).

Table 6.4 The costs of electricity generation, hydrogen production, and second-generation liquid fuels production from biomass in 2020. These costs are adapted from (Daioglou et al. 2020), (Bhave et al. 2017), (NREL 2020a), (Lepage et al. 2021), (Witcover and Williams 2020), (NREL 2020b)

	Unit	Low	Median	High
Bioelectricity with CCS	USD/MWh	74	86	160
Bioelectricity without CCS	USD/MWh	66	84	112
Biohydrogen with CCS*	USD/kg	1.63	2.37	2.41
Biohydrogen without CCS*	USD/kg	1.59	1.79	2.37
Liquid biofuels with CCS	USD/gge	1.34	4.20	7.85
Liquid biofuels without CCS	USD/gge	1.15	4.00	7.60

*** Using cellulosic feedstocks**

- <u>Electricity.</u> The costs of baseload electricity production with biomass are higher than corresponding fossil electricity production with and without CCS, and are likely to remain as such without carbon pricing (Bhave et al. 2017). The additional cost associated with CO_2 capture are high for conventional solvent-based technologies. However, upcoming technologies such as chemical looping are well-suited to biomass and could reduce CCS costs.
- <u>Hydrogen.</u> The costs of hydrogen production from biomass are somewhat higher than, but comparable, to that produced by natural gas reforming with CCS. Further, the incremental costs for incorporating CCS in this process are less than 5% of the levelized costs in some cases, since the

gasification route creates a high-purity stream of CO_2 (Muratori et al. 2017a; Sunny et al. 2020). While these processes have fewer ongoing prototypes/demonstrations, the costs of biomass-based hydrogen (with or without CCS) are substantially cheaper than that produced from electrolysis utilizing solar/wind resources (Kayfeci et al. 2019; Newborough and Cooley 2020), even though electrolysis costs are dropping.

- Liquid Biofuels. First-generation sugar-based biofuels (e.g., ethanol produced via fermentation) or biodiesel produced from vegetable oils and animal fats are produced in several countries at large scale and costs competitive with fossil fuels. However, supply is limited. The costs for second generation processes (Fischer-Tropsch and cellulosic ethanol) are higher in most regions (Li et al. 2019). Technological learning is projected to reduce these costs by half (IEA 2020g).

Large-scale bioenergy production will require more than wastes/residues and cultivation on marginal lands, which may raise conflicts with SDGs relevant to environmental and societal priorities (Gerten et al. 2020; Heck et al. 2018) (Chapter 12). These include competition with food crops, implications for biodiversity, potential deforestation to support bioenergy crop production, energy security implications from bioenergy trade, point-of-use emissions and associated effects on air quality, and water use and fertilizer use (Fajardy and Mac Dowell 2018; Tanzer and Ramírez 2019; Fuss et al. 2018; Brack and King 2020). Overall, the environmental impact of bioenergy production at scale remains uncertain and varies by region and application.

Alleviating these issues would require some combination of increasing crop yields, improving conversion efficiencies, and developing advanced biotechnologies for increasing the fuel yield per tonne of feedstock (Henry et al. 2018). Policy structures would be necessary to retain biodiversity, manage water use, limit deforestation and land-use change emissions, and ultimately optimally integrate bioenergy with transforming ecosystems. Large-scale international trade of biomass might be required to support a global bioeconomy, raising questions about infrastructure, logistics, financing options, and global standards for bioenergy production and trade (Box 6.10). Additional institutional and economic barriers are associated with accounting of carbon dioxide removal, including BECCS (Fuss et al. 2014; Muratori et al. 2016; Fridahl and Lehtveer 2018).

Life-cycle emissions impacts from bioenergy are subject to large uncertainties and could be incompatible with net zero emissions in some contexts. Due to the potentially large energy conversion requirements and associated GHG emissions (Chapter 7, Chapter 12), bioenergy systems may fail to deliver near-zero emissions depending on operating conditions and regional contexts (Staples et al. 2017; Lade et al. 2020; Daioglou et al. 2017; Hanssen et al. 2020; Elshout et al. 2015). As a result, bioenergy carbon neutrality is debated and depends on factors such as the source of biomass, conversion pathways and energy used for production and transport of biomass, and land use changes, as well as assumed analysis boundary and considered timescale (Fan et al. 2021; Wiloso et al. 2016; Zanchi et al. 2012; Booth 2018). Similarly, the lifecycle emissions of BECCS remain uncertain and will depend on how effectively bioenergy conversion processes are optimized (Fajardy and Mac Dowell 2017; Tanzer and Ramírez 2019).

Acceptability of bioenergy is relatively low compared to other renewable energy sources like solar and wind (Poortinga et al. 2013; EPCC 2017; Peterson et al. 2015; Ma et al. 2015) and comparable to natural gas (Scheer et al. 2013). People also know relatively little about bioenergy compared to other energy sources (Whitmarsh et al. 2011a; EPCC 2017) and tend be be more ambivalent towards bioenergy compared to other mitigation options (Allen and Chatterton 2013). People evaluate biomass from waste products (e.g., food waste) more favourably than grown-for-purpose energy crops, which are more controversial (Demski et al. 2015; Plate et al. 2010). The most pressing concerns for use of woody biomass are air pollution and loss of local forests (Plate et al. 2010). Various types of bioenergy additionally raise concerns about landscape impacts (Whitmarsh et al. 2011a) and biodiversity

(Immerzeel et al. 2014). Moreover, many people do not see biomass as a renewable energy source, possibly because it involves burning of material.

START BOX 6.5 HERE

Box 6.5 Methane mitigation options for coal, oil, and gas

Methane emissions mainly from coal, oil, and gas currently represent in 2019 about 18% of energy supply sector GHG emissions and 90% of global energy supply non-CO_2 emissions in 2019 (Minx et al. 2021b). While approximately 80% of the life-cycle methane emissions in the coal sector occur during underground mining, oil and gas emissions are spread throughout upstream, midstream, and downstream stages (IPCC, 2019) (Alvarez et al. 2018). For this reason, methane reductions from coal mining can be accomplished through coal mine methane recovery (where methane and coal are recovered simultaneously) and from the ventilation air, which can reduce methane emissions by 50–75% (Singh and Hajra 2018; Zhou et al. 2016). Governments incentivize such operations through a number of emissions trading and offset programs (Haya et al. 2020). Methane emissions in the oil and gas sector can be reduced by leak detection and repair, relevant across varying time scales (hours to decades) and regional scopes (component/facility level to continental) (Fox et al. 2019). Around 50% of the methane emitted from oil and gas infrastructure can be mitigated at net-negative costs; that is, the market price of the recovered methane is higher than the mitigation costs (IEA 2021e). As CO_2 emissions are reduced and fossil fuel consumption decreases, methane emissions associated with these supply chains are anticipated to decline (section 6.7). That said, substantial 'legacy' methane emissions – methane leaks after abandonment – will remain even if a complete fossil fuel phase-out takes place. These legacy emissions are estimated to be less than 1–4% of overall methane emissions across all fossil fuel sources (Kholod et al. 2020; Williams et al. 2021b). Even without a complete phase-out, 50-80% of methane emissions from coal, oil and gas could be avoided with currently available technologies at less than USD 50 tCO_2-eq^{-1} (Höglund-Isaksson et al. 2020; Harmsen et al. 2019). Methane recovery from abandoned coal mines could offset most project costs (Singh and Sahu 2018). For abandoned oil and gas wells, low plugging costs could be offset through methane recovery, while high plugging costs would likely require some market or policy support (Kang et al. 2019).

[END BOX 6.5 HERE]

6.4.2.7. Fossil Energy

Fossil fuels could play a role in climate change mitigation if strategically deployed with CCS *(high confidence)*. On the one hand, the primary mechanism for reducing emissions is to eliminate the unabated fossil fuel use. On the other hand, fossil energy combined with CCS provides a means of producing low-carbon energy while still utilizing the available base of fossil energy worldwide and limiting stranded assets. While Section 6.4.2.5 discusses the important aspects of CCS with fossil fuels, this section aims to elucidate the feasibility criteria around these fuels itself.

Fossil fuel reserves have continued to rise because of advanced exploration and utilization techniques (*high confidence*). A fraction of these available reserves can be used consistent with mitigation goals when paired with CCS opportunities in close geographical proximity (*high confidence*). Based on continued exploration, the fossil fuel resource base has increased significantly; for example, a 9% increase in gas reserves and 12% in oil reserves was observed in the U.S. between 2017 and 2018. This increase is a result of advanced exploration techniques, which are often subsidized (Lazarus and van Asselt 2018; MA et al. 2018). Fossil reserves are distributed unevenly throughout the globe. Coal represents the largest remaining resource (close to 500 ZJ). Conventional oil and gas resources are an order of magnitude smaller (15–20 ZJ each). Technological advances have increased the reserves of unconventional fossil in the last decade. Discovered ultimate recoverable resources of unconventional oil and gas are comparable to conventional oil and gas (Fizaine et al. 2017).

It is unlikely that resource constraints will lead to a phaseout of fossil fuels, and instead, such a phase-out would require policy action. Around 80% of coal, 50% of gas, and 20% of oil reserves are likely to remain unextractable under 2°C constraints (McGlade and Ekins 2015; Pellegrini et al. 2020). Reserves are more likely to be utilized in a low-carbon transition if they can be paired with CCS. Availability of CCS technology not only allows continued use of fossil fuels as a capital resource for countries but also paves the way for CDR through BECCS (Pye et al. 2020; Haszeldine 2016). While the theoretical geologic CO_2 sequestration potential is vast, there are limits on how much resource base could be utilized based on geologic, engineering, and source-sink mapping criteria (Budinis et al. 2017).

Technological changes have continued to drive down fossil fuel extraction costs. Significant decarbonization potential also exists via diversification of the fossil fuel uses beyond combustion (high evidence). The costs of extracting oil and gas globally have gone down by utilizing hydraulic fracturing and directional drilling for resources in unconventional reservoirs (Wachtmeister and Höök 2020). Although the extraction of these resources is still more expensive than those derived from conventional reservoirs, the large availability of unconventional resources has significantly reduced global prices. The emergence of liquefied natural gas (LNG) markets has also provided opportunities to export natural gas significant distances from the place of production (Avraam et al. 2020). The increase in availability of natural gas has been accompanied by an increase in the production of natural gas liquids as a co-product to oil and gas. Over the period from 2014 to 2019, exports of natural gas liquids increased by 160%. Natural gas liquids could potentially be a lower-carbon alternative to liquid fuels and hydrocarbons. On the demand side, natural gas can be used to produce hydrogen using steam methane reforming, which is a technologically mature process (Sections 6.4.4, 6.4.5). When combined with 90% CO_2 capture, the costs of producing hydrogen are around USD 1.5–2 $kg(H_2)^{-1}$ (Newborough and Cooley 2020; Collodi et al. 2017), considerably less than hydrogen produced via electrolysis.

Significant potential exists for gasifying deep-seated coal deposits *in situ* to produce hydrogen. Doing so reduces fugitive methane emissions from underground coal mining. The integration costs of this process with CCS are less than with natural gas reforming. The extent to which coal gasification could be compatible with low-carbon energy would depend on the rate of CO_2 capture and the ultimate use of the gas (Verma and Kumar 2015). Similarly, for ongoing underground mining projects, coal mine methane recovery can be economic for major coal producers such as China and India. Coal mine methane and ventilation air methane recovery can reduce the fugitive methane emissions by 50–75% (Zhou et al. 2016; Singh and Sahu 2018).

The cost of producing electricity from fossil sources has remained roughly the same with some regional exceptions while the costs of transport fuels has gone down significantly (*high confidence*). The cost of producing electricity from fossil fuels has remained largely static, with the exception of some regional changes, for example, a 40% cost reduction in the U.S. for natural gas (Rai et al. 2019), where the gas wellhead price has declined by almost two-thirds due to large reserves. Similarly, the global price of crude oil has declined from almost USD 100–55 bbl^{-1} in the last five years.

The energy return of investment (EROI) is a useful indicator of full fossil lifecycle costs. Fossil fuels create significantly more energy per unit energy invested – or in other words have much larger EROI – than most cleaner fuels such as biomass or electrolysis-derived hydrogen, where intensive processing reduces EROI (Hall et al. 2014). That said, recent years have seen a decrease in fossil EROI, especially as underground coal mining has continued in China. Exploitation of unconventional gas reservoirs is also energy intensive and has led to a reduction in EROI. The primary energy EROI of fossil fuels has converged at about 30, which represents a 20-point decrease from the 1995 value for coal (Brockway et al. 2019). When processing and refining stages are considered, these EROI values further decrease.

Several countries have large reserves of fossil fuels. Owing to climate constraints, these may become stranded causing considerable economic impacts (6.7.3, 6.7.4, Box 6.13) (*high confidence*). While global fossil energy resources are greater than 600 ZJ, more than half of these resources would likely be unburnable even in the presence of CCS (Pye et al. 2020; McGlade and Ekins 2015). This would entail a significant capital loss for the countries with large reserves. The total amount of stranded assets in such a case would amount to USD 1–4 trillion at present value (Box 6.13).

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

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

Oil and coal consistently rank among the least preferred energy sources in many countries (*high confidence*). The main perceived advantage of fossil energy is the relatively low costs, and emphasizing these costs might increase acceptability somewhat (Pohjolainen et al. 2018; Hazboun and Boudet 2020; Boyd et al. 2019). Acceptability of fossil fuels is on average similar to acceptability of nuclear energy, although evaluations are less polarized. People evaluate natural gas as somewhat more acceptable than other fossil fuels, although they generally oppose hydraulic fracturing (Clarke et al. 2016). Yet, natural gas is evaluated as less acceptable than renewable energy sources, although evaluations of natural gas and biogas are similar (Liebe and Dobers 2019; Plum et al. 2019). Acceptability of fossil energy tends to be higher in countries and regions that strongly rely on them for their energy production (Boyd et al. 2019; Pohjolainen et al. 2018). Combining fossil fuels with CCS can increase their acceptability (Van Rijnsoever et al. 2015; Bessette and Arvai 2018). Some people seem ambivalent about natural gas, as they perceive both benefits (e.g., affordability, less carbon emissions than coal) and disadvantages (e.g., finite resource, contributing to climate change) (Blumer et al. 2018).

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

6.4.2.8 Geothermal Energy

Geothermal energy is heat stored in the Earth's subsurface and is a renewable resource that can be sustainably exploited. The geophysical potential of geothermal resources is 1.3 to 13 times the global electricity demand in 2019 (*medium confidence*). Geothermal energy can be used directly for various thermal applications, including space heating and industrial heat input, or converted to electricity depending on the source temperature (Moya et al. 2018; REN21 2019; Limberger et al. 2018).

Suitable aquifers underlay 16% of the Earth's land surface and store an estimated 110,000–1,400,000 PWh (400,000–1,450,000 EJ) that could theoretically be used for direct heat applications. For electricity generation, the technical potential of geothermal energy is estimated to be between 30 PWh yr^{-1} (108

EJ yr^{-1}) (to 3 km depth) and 300 PWh yr^{-1} (1080 EJ yr^{-1}) (to 10 km depth). For direct thermal uses, the technical potential is estimated to range from 2.7–86 PWh yr^{-1} (9.7–310 EJ yr^{-1})(IPCC 2011). Despite the potential, geothermal direct heat supplies only 0.15% of the annual global final energy consumption. The technical potential for electricity generation, depending on the depth, can meet one third to almost three times the global final consumption (based on IEA database for IPCC). The mismatch between potential and developed geothermal resources is caused by high up-front costs, decentralized geothermal heat production, lack of uniformity among geothermal projects, geological uncertainties, and geotechnical risks (IRENA 2017a; Limberger et al. 2018). A limited number of countries have a long history in geothermal. At least in two countries (Iceland and New Zealand), geothermal accounts for 20–25% of electricity generation (Spittler et al. 2020; Pan et al. 2019). Furthermore, in Iceland approximately 90% of the households are heated with geothermal energy. In Kenya, as of July 2019, geothermal accounted for 734 MW effective capacity spread over 10 power plants and approximately one third of the total installed capacity (Kahlen 2019).

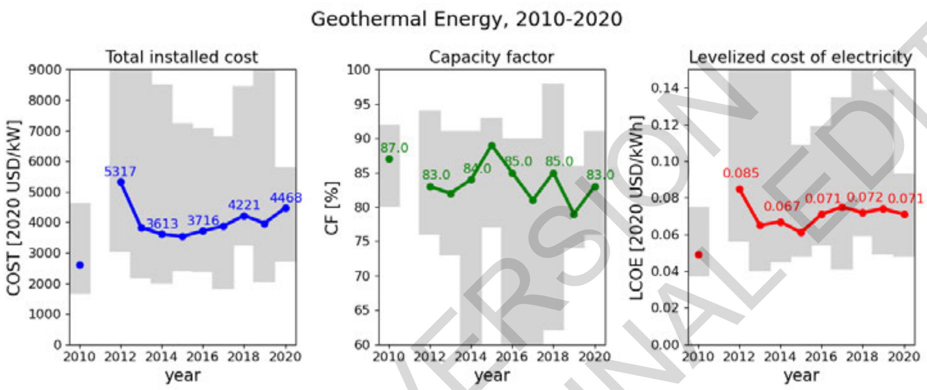


Figure 6.15 Global weighted average total installed costs, capacity factors and LCOE for geothermal power per year (2010-2020). The shaded area represents the 5% and 95% percentiles. Source: (IRENA 2021a)

There are two main types of geothermal resources: convective hydrothermal resources, in which the Earth's heat is carried by natural hot water or steam to the surface, and hot, dry rock resources, in which heat cannot be extracted 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 increasingly used for electricity generation or combined heat and power. The use of medium temperature fields has been enabled through the development of binary cycle technology, in which a geothermal fluid is used via heat exchangers. Increasing binary generation technologies are now being utilized instead of flash steam power plants. This will result in almost 100% injection and essentially zero GHG emissions, although GHG emissions from geothermal power production are generally small compared to traditional baseload thermal energy power generation facilities (Fridriksson et al. 2016).

Additionally, new technologies are being developed like Enhanced Geothermal Systems (EGS), which is in the demonstration stage (IRENA 2018), deep geothermal technology, which may increase the prospects for harnessing the geothermal potential in a large number of countries, or shallow-geothermal energy, which represents a promising supply source for heating and cooling buildings (Narsilio and Aye 2018). Successful large-scale deployment of shallow geothermal energy will depend not only on site-specific economic performance but also on developing suitable governance frameworks (Bloemendal et al. 2018; García-Gil et al. 2020). Technologies for direct uses like district heating, geothermal heat pumps, greenhouses, and other applications are widely used and considered mature. Given the limited number of plants commissioned, economic indicators (Figure 6.15) vary considerably depending on site characteristics.

Public awareness and knowledge of geothermal energy is relatively low *(high confidence)*. Geothermal energy is evaluated as less acceptable than other renewable energy sources such as solar and wind, but is preferred over fossil and nuclear energy, and in some studies, over hydroelectric energy (Karytsas et al. 2019; Pellizzone et al. 2015; Steel et al. 2015; Hazboun and Boudet 2020) (*high confidence*). Some people are concerned about the installation of geothermal facilities close to their homes, similar to solar and wind projects (Pellizzone et al. 2015). The main concerns about geothermal energy, particularly for large scale, high-temperature geothermal power generation plants, involve water usage, water scarcity, and seismic risks of drilling (Dowd et al. 2011). Moreover, noise, smell and damages to the landscape have been reasons for protests against specific projects (Walker 1995). However, with the implementation of modern technologies, geothermal presents fewer adverse environmental impacts. At the same time, people perceive geothermal energy as relatively environmentally friendly (Tampakis et al. 2013).

6.4.2.9 Marine Energy

The ocean is a vast source of energy (Hoegh-Guldberg et al. 2019). Ocean energy can be extracted from tides, waves, ocean thermal energy conversion (OTEC), currents, and salinity gradients (Bindoff et al. 2019). Their technical potentials, without considering possible exclusion zones, are explored below. Tidal energy, which uses elevation differences between high and low tides, appears in two forms: potential energy (rise and fall of the tide) and current energy (from tidal currents). The global technically harvestable tidal power from areas close to the coast is estimated as ~1.2 PWh yr^{-1} (4.3 EJ yr^{-1}) (IRENA 2020b). The potential for tidal current energy is estimated to be larger than that for tidal range or barrage (Melikoglu 2018). Ocean wave energy is abundant and predictable and can be extracted directly from surface waves or pressure fluctuations below the surface (Melikoglu 2018). Its global theoretical potential is 29.5 PWh yr^{-1} (106 EJ yr^{-1}) ,which means that wave energy alone could meet all global energy demand (Mørk et al. 2010; IRENA 2020b). The temperature gradients in the ocean can be exploited to produce energy, and its total estimated available resource could be up to 44.0 PWh yr^{-1} (158 EJ yr^{-1}) (Rajagopalan and Nihous 2013). Salinity gradient energy, also known as osmotic power, has a global theoretical potential of over 1.6 PWh yr^{-1} (6.0 EJ yr^{-1}) (IRENA 2020b). The greatest advantage of most marine energy, excluding wave energy, is that their sources are highly regular and predictable, and energy can be furthermore generated both day and night. An additional use of sea water is to develop lower-cost district cooling systems near the sea (Hunt et al. 2019). The greatest barrier to most marine technology advances is the relatively high upfront costs, uncertainty on environmental regulation and impact, need for investments and insufficient infrastructure (Kempener and Neumann 2014a,b). There are also concerns about technology maturity and performance; thus, not all have the potential to become economically viable (IRENA 2020b).

6.4.2.10 Waste-to-Energy

Waste-to-energy (WTE) is a strategy to recover energy from waste in a form of consumable heat, electricity, or fuel (Zhao et al. 2016). Thermal (incineration, gasification, and pyrolysis) and biological (anaerobic digestion and landfill gas to energy) technologies are commonly used (Ahmad et al. 2020).When WTE technologies are equipped with proper air pollution reduction facilities they can contribute to clean electricity production and reduction of GHG emissions. However, if not properly operated, they can exacerbate air quality issues.

In 2019, there were more than 1,200 WTE incineration facilities worldwide, with estimated capacity of 310 million tons per year (UNECE 2020). It is estimated that treatment of a minimum of 261 million tons/year of waste could produce 283 TWh (1 EJ) of power and heat by 2022 (Awasthi et al., 2019). Incineration plants can reduce the mass of waste by 70%-80% and the volume of waste by 80%-90% (Haraguchi et al. 2019). Incineration technology can reduce water and soil pollution (Gu et al., 2019). However, if not properly handled, dust, and gases such as SO_2, HCL, HF, NO_2, and dioxins in the flue gases can harm the environment (Mutz et al. 2017). Anaerobic digestion technology has a positive environmental impact and the ability to reduce GHG emissions (Ayodele et al. 2018; Cudjoe et al. 2020). The by-product of the anaerobic digestion process could be used as a nutrient-rich fertilizer for enhancing soil richness for agricultural purposes (Wainaina et al. 2020). Due to the potential negative impacts on domestic environment and residents' health, WTE projects such as incineration encounter substantial opposition from the local communities in which they are located (Ren et al., 2016; Baxter et al., 2016). Therefore, for WTE to be deployed more widely, policies would need to be tailored with specific guidelines focused on mitigating emissions, which may have adverse effect on the environment.

Depending on the origin of the waste used, the integration of WTE and carbon capture and storage (CCS) could enable waste to be a net zero or even net negative emissions energy source (Kearns 2019; Wienchol et al. 2020). For example, in Europe only, the integration of CCS with WTE facilities has the potential to capture about 60 to 70 million tons of carbon dioxide annually (Tota et al. 2021).

Waste-to-energy is an expensive process compared to other energy sources such as fossil fuels and natural gas (Mohammadi and Harjunkoski 2020). However, the environmental and economic benefits make its high financial costs justifiable. In 2019, the global WTE market size was valued at USD 31 billion, and it is predicted to experience 7.4% annual growth until 2027 (UNECE 2020).

6.4.3 Energy System Integration

Greenhouse gases are emitted across all economic activities. Therefore, cost-effective decarbonization requires a "system of systems" approach that considers the interaction between different energy sectors and systems. Flexibility technologies and advanced control of integrated energy systems (e.g., considering the interaction between electricity, heating/cooling, gas/hydrogen, transport sectors) could reduce energy infrastructure investments substantially in future low-carbon energy systems (Strbac et al. 2015b; Jacobson et al. 2019)

The electricity grid will serve as a backbone of future low-carbon energy systems. Integration of large amounts of VRE generation (Hansen et al. 2019), particularly wind and solar generation (Perez et al. 2019; Bistline and Young 2019), presents economic and technical challenges to electricity system management across different timescales from sub-seconds, hours, days, seasons, to multiple years. Furthermore, electrification of segments of the transport and heat sectors could disproportionately increase peak demand relative to supply (Bistline et al. 2021). Increases in peak demand may require reinforcing network infrastructures and generation in the historical passive system operation paradigm (Strbac et al. 2020).

These challenges to electricity system management can be addressed through system integration and a digitalized control paradigm involving advanced information and communication technologies. Real-time maintenance of supply-demand balance and sufficient flexibility technologies such as electricity storage, flexible demand, and grid forming converters (Strbac et al. 2015a; López Prol and Schill 2021) would be increasingly valuable for incorporating larger amounts of VRE generation. This flexibility will be particularly important to deal with sudden losses of supply, for example, due to a failure of a large generator or interconnector or a rapid increase in demand (Teng et al. 2017; Chamorro et al. 2020).

The transition to a digitalized-based electricity system control paradigm would facilitate radical changes in the security of supply, moving from the traditional approach of redundancy in assets to a smart control paradigm. Advanced control and communication systems can significantly reduce the electricity system investment and operation costs (2020; Münster et al. 2020; Harper et al. 2018).

Importance of cross-sector coupling for cost-effective energy system decarbonization

Integrated whole-system approaches can reduce the costs of low-carbon energy system transitions (*high confidence*). A lack of flexibility in the electricity system may limit the cost-effective integration of technologies as part of broader net zero energy systems. At the same time, the enormous latent flexibility hidden in heating and cooling, hydrogen, transport, gas systems, and other energy systems provides opportunities to take advantage of synergies and to coordinate operations across systems (Martinez Cesena and Mancarella 2019; Zhang et al. 2018; Bogdanov et al. 2021; Pavičević et al. 2020; Martin et al. 2017) (Figure 6.16).

Sector coupling can significantly increase system flexibility, driven by the application of advanced technologies (Bogdanov et al. 2019; Solomon et al. 2019; Clegg and Mancarella 2016; Zhang and Fujimori 2020; Zhao et al. 2021; Heinen et al. 2016; Zhang et al. 2019b). For example, district heating infrastructure can generate both heat and power. Cooling systems and electrified heating systems in buildings can provide flexibility through preheating and precooling via thermal energy storage Li, G. et al. 2017; Li, Z. et al. 2016).. System balancing services can be provided by electric vehicles (EVs) based on vehicle-to-grid concepts and deferred charging through smart control of EV batteries without compromising customers' requirements for transport (Aunedi and Strbac 2020).

Hydrogen production processes (power-to-gas and vice versa) and hydrogen storage can support short-term and long-term balancing in the energy systems and enhance resilience (Stephen and Pierluigi 2016; Strbac et al. 2020). However, the economic benefits of flexible power-to-gas plants, energy storage, and other flexibility technological and options will depend on the locations of VRE sources, storage sites, gas, hydrogen, and electricity networks (Jentsch et al. 2014; Heymann and Bessa 2015; Ameli et al. 2020). Coordinated operation of gas and electricity systems can bring significant benefits in supplying heat demands. For example, hybrid heating can eliminate investment in electricity infrastructure reinforcement by switching to heat pumps in off-peak hours and gas boilers in peak hours (Dengiz et al. 2019; Fischer et al. 2017; Bistline et al. 2021). The heat required by direct air carbon capture and storage (DACCS) could be effectively supplied by inherent heat energy in nuclear plants, enhancing overall system efficiency (Realmonte et al. 2019).

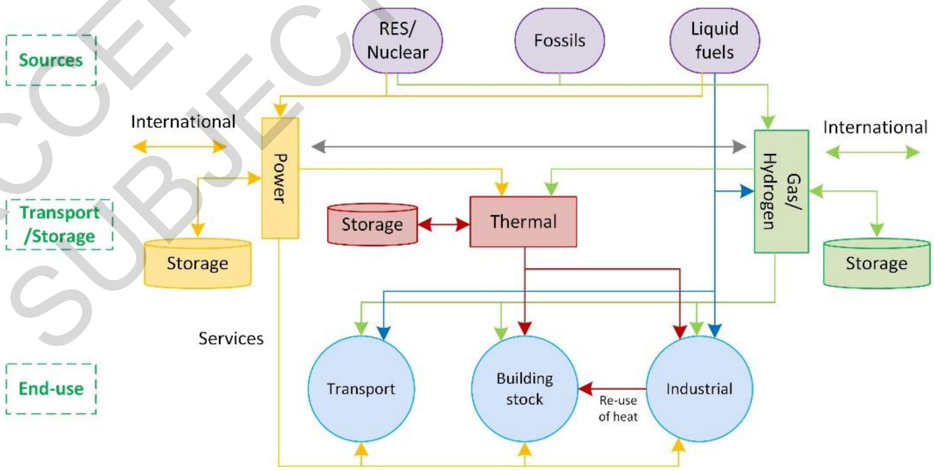


Figure 6.16 Interaction between different energy sectors (extracted from Münster et al. 2020)

Rather than incremental planning, strategic energy system planning can help minimize long-term mitigation costs (*high confidence*). With a whole-system perspective, integrated planning can consider both short-term operation and long-term investment decisions, covering infrastructure from local to national and international, while meeting security of supply requirements and incorporating the flexibility provided by different technologies and advanced control strategies (Zhang et al. 2018; O'Malley et al. 2020; Strbac et al. 2020). Management of conflicts and synergies between local district and national level energy system objectives, including strategic investment in local hydrogen and heat infrastructure, can drive significant whole-system cost savings (Fu et al. 2020; Zhang et al. 2019b). For example, long-term planning of the offshore grid infrastructure to support offshore wind development, including interconnection between different countries and regions, can provide significant savings compared to a short-term incremental approach in which every offshore wind farm is individually connected to the onshore grid (E3G 2021).

6.4.3.1 Role of flexibility technologies

Flexibility technologies - including energy storage, demand-side response, flexible/dispatchable generation, grid forming converters, and transmission interconnection - as well as advanced control systems, can facilitate cost-effective and secure low-carbon energy systems (*high confidence*). Flexibility technologies have already been implemented, but they can be enhanced and deployed more widely. Due to their interdependencies and similarities, there can be both synergies and conflicts for utilizing these flexibility options (Bistline et al. 2021). It will therefore be important to coordinate the deployment of the potential flexibility technologies and smart control strategies. Important electricity system flexibility options include the following:

- *Flexible/dispatchable generation:* Advances in generation technologies, for example, gas/hydrogen plants and nuclear plants, can enable them to provide flexibility services. These technologies would start more quickly, operate at lower power output, and make faster output changes, enabling more secure and cost-effective integration of VRE generation and end-use electrification. There are already important developments in increasing nuclear plants flexibility (e.g., in France (Office of Nuclear Energy 2021)) and the development of small modular reactors, which could support system balancing (FTI Consulting 2018).
- *Grid-forming converters (inverters):* The transition from conventional electricity generation, applying mainly synchronous machines to inverter-dominated renewable generation, creates significant operating challenges. These challenges are mainly associated with reduced synchronous inertia, system stability, and black start capability. Grid-forming converters will be a cornerstone for the control of future electricity systems dominated by VRE generation. These converters will address critical stability challenges, including the lack of system inertia, frequency and voltage regulation, and black-start services while reducing or eliminating the need to operate conventional generation (Tayyebi et al. 2019).
- *Interconnection:* Electricity interconnections between different regions can facilitate more cost-effective renewable electricity deployment. Interconnection can enable large-scale sharing of energy and provide balancing services. Back-up energy carriers beyond electricity, such as ammonia, can be shared through gas/ammonia/hydrogen-based interconnections, strengthening temporal coupling of multiple sectors in different regions (Bhagwat et al. 2017; Brown et al. 2018) (Section 6.4.5).
- *Demand-side response:* Demand-side schemes – including, for example, smart appliances, EVs, and building-based thermal energy storage (Heleno et al. 2014) – can provide flexibility services across multiple time frames and systems. Through differentiation between essential and non-essential needs during emergency conditions, smart control of demands can significantly enhance system resilience (Chaffey 2016).
- *Energy storage:* Energy storage technologies (Section 6.4.4) can act as both demand and generation sources. They can provide services such as system balancing, various ancillary services, and network management. Long-duration energy storage can significantly enhance the utilization of renewable energy sources and reduce the need for firm low-carbon generation (Sepulveda et al. 2021).

6.4.3.2 Role of digitalization and advanced control systems

A digitalized energy system can significantly reduce energy infrastructure investments while enhancing supply security and resilience (*high confidence*) (Andoni et al. 2019; Strbac et al. 2020). Significant progress has been made in the development of technologies essential for the transition to a digitalized energy control paradigm, although the full implementation is still under development. Electrification and the increased integration of the electricity system with other systems will fundamentally transform the operational and planning paradigm of future energy infrastructure. A fully intelligent and sophisticated coordination of the multiple systems through smart control will support this paradigm shift. This shift will provide significant savings through better utilization of existing infrastructure locally, regionally, nationally, and internationally. Supply system reliability will be enhanced through advanced control of local infrastructure (Strbac et al. 2015a). Furthermore, this paradigm shift offers the potential to increase energy efficiency through a combination of technologies that gather and analyse data and consequently optimize energy use in real-time.

The transition to advanced data-driven control of energy system operations (Sun et al. 2019a; Cremer et al. 2019) will require advanced information and communication technologies and infrastructure, including the internet, wireless networks, computers, software, middleware, smart sensors, internet of things components, and dedicated technological developments (Hossein Motlagh et al. 2020). The transition will raise standardization and cybersecurity issues, given that digitalization can become a single point of failure for the complete system (Unsal et al. 2021; Ustun and Hussain 2019). Implementing peer-to-peer energy trading based on blockchain is expected to be one of the key elements of next-generation electricity systems (Qiu et al. 2021). This trading will enable consumers to drive system operation and future design, increasing overall system efficiency and security of supply while reducing emissions without sacrificing users' privacy (Andoni et al. 2019; Ahl et al. 2020). When deployed with smart contracts, this concept will be suitable for energy systems involving many participants, where a prerequisite is digitalization (e.g., smart meters, end-use demand control systems) (Teufel et al. 2019; Juhar and Khaled 2018).

6.4.3.3 System benefits of flexibility technologies and advanced control systems

New sources of flexibility and advanced control systems provide a significant opportunity to reduce low-carbon energy system costs by enhancing operating efficiency and reducing energy infrastructure and low-carbon generation investments, while continuing to meet security requirements (*high confidence*). In the U.S, for example, one study found that flexibility in buildings alone could reduce U.S. CO_2 emissions by 80 MT yr^{-1} and save USD 18 bn yr^{-1} in electricity system costs by 2030 (Satchwell et al. 2021). Key means for creating savings are associated with the following:

- *Efficient energy system operation*: Flexibility technologies such as storage, demand-side response, interconnection, and cross-system control will enable more efficient, real-time demand and supply balancing. This balancing has historically been provided by conventional fossil-fuel generation (Nuytten et al. 2013).
- *Savings in investment in low carbon/renewable generation capacity:* System flexibility sources can absorb or export surplus electricity, thus reducing or avoiding energy curtailment and reducing the need for firm low-carbon capacity such as nuclear and fossil-fuel plants with CCS (Newbery et al. 2013; Solomon et al. 2019). For example, one study found that flexibility technologies and advanced control systems could reduce the need for nuclear power by 14 GW and offshore wind by 20 GW in the UK's low-carbon transition (Strbac et al. 2015b).
- *Reduced need for backup capacity:* System flexibility can reduce energy demand peaks, reducing the required generation capacity to maintain the security of supply, producing significant savings in generation investments (Strbac et al. 2020).
- *Deferral or avoidance of electricity network reinforcement/addition:* Flexibility technologies supported by advanced control systems can provide significant savings in investment in electricity

network reinforcement that might emerge from increased demand, for example, driven by electrification of transport and heat sectors. Historical network planning and operation standards are being revised considering alternative flexibility technologies, which would further support cost-effective integration of decarbonized transport and heat sectors (Strbac et al. 2020).

6.4.4 Energy Storage for Low-Carbon Grids

Energy storage technologies make low carbon electricity systems more cost-effective, allowing VRE technologies to replace more expensive firm low carbon generation technologies (Carbon Trust 2016) and reducing investment costs in backup generation, interconnection, transmission, and distribution network upgrades (*high confidence*). Energy system decarbonization relies on increased electrification (Section 6.6.2.3.). Meeting increasing demands with variable renewable sources presents challenges and could lead to costly infrastructure reinforcements. Energy storage enables electricity from variable renewables to be matched against evolving demands across both time and space, using short-, medium- and long-term storage of excess energy for delivery later or different location. In 2017, an estimated 4.67 TWh (0.017 EJ) of electricity storage was in operation globally (IRENA 2017). If the integration of renewables is doubled from 2014 levels by 2030, the total capacity of global electricity storage could triple, reaching 11.89–15.27 TWh (0.043–0.055 EJ)(IRENA 2017b).

Table 6.5 Suitability of low carbon energy storage technologies, in terms of the grid services they can provide, and overall features such as technology maturity, where Low represents an emerging technology; Med represents a maturing technology and High a fully mature technology. The opportunity for the cost of a technology to reduce over the next decade is represented by Low, Med and High and the lifetime of installations by: Long, for projects lasting more than 25 years; Med for those lasting 15–25 years; Short, for those lasting less than 15 years. (PHS - Pumped Hydroelectric Storage, CAES - Compressed Air Energy Storage, LAES - Liquid Air Energy Storage, TES - Thermal Energy Storage, FES - Flywheel Energy Storage, LiB – Li-ion Batteries, Scap – Supercapacitors, RFB - Redox Flow Batteries, RHFC - Reversible Hydrogen Fuel Cells, PtX – Power to fuels). [Footnote: References: PHS – IRENA 2017, Barbour et al. 2016, Yang 2016; CAES – Brandon et al. 2015, IRENA 2017, Luo et al. 2014; LAES – Luo et al. 2014, Highview 2019; TES – Brandon et al. 2015, Smallbone et al. 2017, Gallo et al. 2016; FES – Yulong et al. 2017, IRENA 2017; LiB – IRENA 2017, Hammond and Hazeldine 2015, Staffell, I. and Rustomji, M. et al. 2016, Schmidt et al. 2017c,Nykvist and Nilsson 2015, May et al. 2018, IRENA 2015b; Scap – Brandon et al. 2015, Gur 2018; RFB – IRENA 2017; RHFC – Gur 2018, IEA 2015]

Suitability factor	PHS	CAES	LAES	TES	FES	LiB	Scap	RFB	PtX	RHFC
Upgrade deferral	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Energy Arbitrage	✓	✓	✓	✓		✓		✓	✓	✓
Capacity firming	✓	✓	✓	✓	✓	✓		✓	✓	✓
Seasonal storage				✓					✓	✓
Stability	✓				✓	✓	✓	✓	✓	✓
Frequency regulation	✓	✓	✓		✓	✓	✓	✓	✓	✓
Voltage support	✓	✓	✓		✓	✓	✓	✓	✓	✓
Black start	✓	✓	✓			✓		✓	✓	✓
Short term reserve	✓	✓	✓			✓		✓	✓	✓
Fast reserve	✓	✓	✓		✓	✓		✓	✓	✓
Islanding		✓	✓	✓		✓		✓	✓	✓
Uninterruptible power supply					✓	✓	✓	✓		✓
Maturity	High	High	Med	Low	High	Med	Low	Low	Low	Low

Opportunity to reduce costs	Low	Low	Low	Med	Med	High	High	High	Med	High
Lifetime	Long	Long	Long	Long	Med	Short	Med	Med	Med	Short
Roundtrip Efficiency	60–80%	30–60%	55–90%	70–80%	90%	>95%	>95 %	80–90%	35–60%	<30%

Energy storage technologies can provide a range of different grid services (Table 6.5). Energy storage enhances security of supply by providing real time system regulation services (voltage support, frequency regulation, fast reserve, and short-term reserve). A greater proportion of variable renewable sources reduces system inertia, requiring more urgent responses to changes in system frequency, which rapid response storage technologies can provide (stability requires responses within sub second timescale for provision of frequency and voltage control services). Energy storage also provides intermittent renewable sources with flexibility, allowing them to contribute a greater proportion of electrical energy and avoiding curtailment (capacity firming). Investment costs in backup generation, interconnection, transmission, and distribution network upgrades can thus be reduced (upgrade deferral), meaning that less low carbon generation will need to be built while still reducing emissions. In the event of an outage, energy storage reserves can keep critical services running (islanding) and restart the grid (black start). The ability to store and release energy as required provides a range of market opportunities for buying and selling of energy (arbitrage).

No single, sufficiently mature energy storage technology can provide all the required grid services - a portfolio of complementary technologies working together can provide the optimum solution (*high confidence*). Different energy storage technologies can provide these services and support cost-effective energy system decarbonization (Carbon Trust 2016). To achieve very low carbon systems, significant volumes of storage will be required (Strbac et al. 2015a; Section 0). There are few mature global supply chains for many of the less-developed energy storage technologies. This means that although costs today may be relatively high, there are significant opportunities for future cost reductions, both through technology innovation and through manufacturing scale. Adding significant amounts of storage will reduce the price variation and, therefore, the profitability of additional and existing storage, increasing investment risk.

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

6.4.4.1 Energy Storage Technologies

<u>Pumped Hydroelectric Storage (PHS).</u> PHS makes use of gravitational potential energy, using water as the medium. Water is pumped into an elevated reservoir using off-peak electricity and stored for later release when electricity is needed. These closed-loop hydropower plants have been in use for decades and account for 97% of worldwide electricity storage capacity (IEA, 2018b; IRENA, 2017). PHS is best suited to balancing daily energy needs at a large scale, and advances in the technology now allow both rapid response and power regulation in both generating and pumping mode (Valavi and Nysveen 2018; Kougias et al. 2019; Dong et al. 2019). The construction itself can cause disruption to the local community and environment (Hayes et al. 2019), the initial investment is costly, and extended

construction periods delay return on investment (Section 6.4.2.3). In addition, locations for large-scale PHS plants are limited.

Advanced pump-turbines are being developed, allowing both reversible and variable-speed operation, supporting frequency control and grid stability with improved round-trip efficiencies (Ardizzon et al. 2014). New possibilities are being explored for small-scale PHS installations and expanding the potential for siting (Kougias et al. 2019). For example, in underwater PHS, the upper reservoir is the sea, and the lower is a hollow deposit at the seabed. Seawater is pumped out of the deposit to store off-peak energy and re-enters through turbines to recharge it (Kougias et al. 2019). Using a similar concept, underground siting in abandoned mines and caverns could be developed reasonably quickly (IEA 2020h). Storage of energy as gravitational potential can also be implemented using materials other than water, such as rocks and sand. Pumped technology is a mature technology (Barbour et al. 2016; Rehman et al. 2015) and can be important in supporting the transition to future low carbon electricity grids (IHA 2021).

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

Table 6.6 Technical characteristics of a selected range of battery chemistries, categorized as those which precede LIBs (white background), LIBs (yellow background) and post LIBs (blue background). With the exception of the All Solid-State batteries, all use liquid electrolytes. (1 =Mahmoudzadeh et al. 2017; 2 = Manzetti and Mariasiu 2015; 3 =Placke et al. 2017; 4 = Nykvist and Nilsson 2015; 5 =Cano et al. 2018; 6 = BloombergENF 2019; 7 = You and Manthiram 2017; 8 = Fotouhi et al. 2017; 9 = IRENA 2017; 10 = Yang et al., 2020)

Battery Type	Technology Maturity	Life Span (Cycles)	Energy Density (Wh L^{-1})	Specific Energy (Wh kg^{-1})	Price (USD kWh^{-1}) in 2017
Lead Acid	High	300–800 [5]	102–106 [5]	38–60 [5]	70–160 [5]
Ni MH	High	600–1200 [5]	220–250 [5]	42–110 [5]	210–365 [5]
Ni Cd	High	1350 [2]	100 [2]	60 [2]	700
High-temperature Na batteries	High	1000 [5]	150–280 [8]	80–120 [1]	315–490 [8]
LIB state of the art	High	1000–6000 [5]	200–680 [3]	110–250 [3]	176 [6]
LIB energy-optimized	Under Development		600–850 [3]	300-440 [3]	
Classic Li Metal (CLIM)	Under Development		800–1050 [3]	420–530 [3]	
Metal Sulfur (Li S)	Near Commercialization	100–500 [5]	350–680 [3, 8]	360–560 [3, 8]	36–130 [5]
Metal Sulfur (Na S)	Under Development	5000–10,000 [8]			
Metal Air (Li/air)	Under Development	20–100 [5]		470–900 [4]	70–200 [5]

Metal Air (Zn/air)	Under Development	150–450 [5]		200–410 [4]	70–160 [5]
Na ion	Under Development	500 [7]		600 [7]	
All-Solid-State	Under Development			278–479 [3]	
Redox	Under Development	>12,000–14,000 [10]	15–25[10]	10–20[10]	66[10]

Drawbacks of batteries include relatively short lifespans and the use of hazardous or costly materials in some variants. While LIB costs are decreasing (Schmidt et al. 2017; Vartiainen et al. 2020), the risk of thermal runaway, which could ignite a fire (Gur 2018; Wang et al. 2019a), concerns about long-term resource availability (Sun et al. 2017; Olivetti et al. 2017), and concerns about global cradle-to-grave impacts (Peters et al. 2017; Kallitsis et al. 2020) need to be addressed.

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

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

CAES is a mature technology in use since the 1970s. Although CAES technologies have been developed, there are not many installations at present (Blanc et al. 2020; Wang et al. 2017b). While the opportunities for CAES are significant, with a global geological storage potential of about 6.5 PW (Aghahosseini and Breyer 2018), a significant amount of initial investment is required. Higher efficiencies and energy densities can be achieved by exploiting the hydrostatic pressure of deep water to compress air within submersible reservoirs (Pimm et al. 2014). CAES is best suited to bulk diurnal electricity storage for buffering VRE sources and services, which do not need a very rapid response. In contrast to PHS, CAES has far more siting options and poses few environmental impacts.

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

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

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

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

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

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

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

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

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

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

Power to fuels (PtX). (see also Section 6.4.3.1) The process of using electricity to generate a gaseous fuel, such as hydrogen or ammonia, is termed power-to-gas (PtG/P2G) (IEA 2020h). When injected into the existing gas infrastructure (section 6.4.5), it has the added benefit of decarbonizing gas (Brandon et al. 2015). Electricity can be used to generate hydrogen, which is then converted back into electricity using combined-cycle gas turbines that have been converted to run on hydrogen. For greater compatibility with existing gas systems and appliances, the hydrogen can combined with captured carbon dioxide to form methane and other synthetic fuels (Thema et al. 2019), however methane has high global warming potential and its supply chain emissions have been found to be significant (Balcombe et al. 2013).

PtX can provide all required grid services, depending on how it is integrated. However, a significant amount of PtX is required for storage to produce electricity again (Bogdanov et al. 2019) due to the low roundtrip efficiency of converting electricity to fuel and back again. However, portable fuels (hydrogen, methane, ammonia, synthetic hydrocarbons) are useful in certain applications, for example in energy systems lacking the potential for renewables, and the high energy density of chemical storage is essential for more demanding applications, such as transporting heavy goods and heating or cooling buildings (IEA 2020h). Research into more efficient and flexible electrolyzers which last longer and cost less is needed (Brandon et al. 2015).

Hydrogen and Reversible Hydrogen Fuel Cells (H/RHFC). Hydrogen is a flexible fuel with diverse uses, capable of providing electricity, heat, and long-term energy storage for grids, industry, and transport, and has been widely used industrially for decades (Section 0). Hydrogen can be produced in various ways and stored in significant quantities in geological formations at moderate pressures, often for long periods, providing seasonal storage (Gabrielli et al. 2020). A core and emerging implementation of PtX is hydrogen production through electrolyzers. Hydrogen is a carbon-free fuel holding three times the energy held by an equivalent mass of gasoline but occupying a larger volume. An electrolyzer uses excess electricity to split water into hydrogen and oxygen through the process of electrolysis. A fuel cell performs the reverse process of recombining hydrogen and oxygen back into water, converting chemical energy into electricity (Elzinga et al. 2014). Reversible hydrogen fuel cells (RHFCs) can perform both functions in a single device, however they are still in the pre-commercial stage, due to prohibitive production costs.

Hydrogen can play an important role in reducing emissions and has been shown to be the most cost-effective option in some cases, as it builds on existing systems (Staffell et al. 2018). Fuel cell costs need to be reduced and the harmonies between hydrogen and complementary technologies, such as batteries, for specific applications need to be explored further. Hydrogen can provide long duration storage to deal with prolonged extreme events, such as very low output of wind generation, to support resilience of future low carbon energy systems. Research in this technology focuses on improving roundtrip efficiencies, which can be as high as 80% with recycled waste heat and in high-pressure electrolyzers, incorporating more efficient compression (Matos et al. 2019). Photo-electrolysis uses solar energy to directly generate hydrogen from water (Amirante et al. 2017).

6.4.4.2 Societal Dimensions of Energy Storage

Public awareness knowledge about electricity storage technologies, their current state, and their potential role in future energy systems is limited (Jones et al. 2018). For instance, people do not perceive energy system flexibility and storage as a significant issue, or assume storage is already taking place. Public perceptions differ across storage technologies. Hydrogen is considered a modern and clean technology, but people also have safety concerns. Moreover, the public is uncertain about hydrogen storage size and the possibility of storing hydrogen in or near residential areas (Eitan and Fischhendler 2021). Battery storage both on the household and community level was perceived as slightly positive in one study in the UK (Ambrosio-Albala et al. 2020). However, financial costs are seen as a main barrier. The potential of electric vehicle batteries to function as flexible storage is limited by the current numbers of EV owners and concerns that one's car battery might not be fully loaded when needed.

6.4.5 Energy Transport and Transmission

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

6.4.5.1 Hydrogen: Low-Carbon Energy Fuel

Hydrogen is a promising energy carrier for a decarbonized world (Box 6.9). It can be utilized for electricity, heat, transport, industrial demand, and energy storage (Abdin et al. 2020). In low-carbon energy systems, hydrogen is expected to be utilized in applications that are not as amenable to electrification, such as a fuel for heavy-duty road transport and shipping, or as a chemical feedstock (Griffiths et al. 2021; Schemme et al. 2017). Hydrogen could also provide low-carbon heat for industrial processes or be utilized for direct reduction of iron ore (Vogl et al. 2018). Hydrogen could replace natural gas-based electricity generation (do Sacramento et al. 2013) in certain regions and support the integration of variable renewables into electricity systems by providing a means of long-term electricity storage. Hydrogen-based carriers, such as ammonia and synthetic hydrocarbons, can likewise be used in energy-intensive industries and the transport sector (Schemme et al. 2017; IRENA 2019b) (e.g., synthetic fuels for aviation). These hydrogen-based energy carriers are easier to store than hydrogen. At present hydrogen has limited applications – mainly being produced onsite for the creation of methanol and ammonia (IEA 2019c), as well as in refineries.

Low- or zero-carbon produced hydrogen is not currently competitive for large-scale applications, but it is likely to have a significant role in future energy systems, due to its wide-range of applications (*high confidence*). Key challenges for hydrogen are: (a) cost-effective low/zero carbon production, (b) delivery infrastructure cost, (c) land area (i.e., 'footprint') requirements of hydrogen pipelines, compressor stations, and other infrastructure, (d) challenges in using existing pipeline infrastructure, (e) maintaining hydrogen purity, (e) minimizing hydrogen leakage, and (f) the cost and performance of end-uses. Furthermore, it is necessary to consider the public perception and social acceptance of hydrogen technologies and their related infrastructure requirements (Scott and Powells 2020; Iribarren et al. 2016)

Hydrogen Production. Low- or zero-carbon hydrogen can be produced from multiple sources. While there is no consensus on the hydrogen production spectrum, "blue" hydrogen (Goldmann and

Dinkelacker 2018) generally refers to hydrogen produced from natural gas combined with CCS through processes such as steam methane reforming (SMR)(Sanusi and Mokheimer 2019) and advanced gas reforming (Zhou et al. 2020). Low-carbon hydrogen could also be produced from coal coupled with CCS (Hu et al. 2020) (Table 6.7). Current estimates are that adding CCS to produce hydrogen from SMR will add on average 50% on the capital cost, 10% to fuel, and 100% to operating costs. For coal gasification, CCS will add 5% to the capital and fuel costs and 130% to operating costs (IEA 2019d; Staffell et al. 2018). Further, biomass gasification could produce renewable hydrogen, and when joined with CCS could provide negative carbon emissions. “Green” hydrogen (Jaszczur et al. 2016) most often is referred to as hydrogen produced from zero-carbon electricity sources such as solar power and wind power (Schmidt et al. 2017) (Table 6.8). Nuclear power could also provide clean hydrogen, via electrolysis or thermochemical water splitting (EERE 2020). Hydrogen can even be produced pyrolysis of methane (Sánchez-Bastardo et al. 2020), sometimes called as “turquoise” hydrogen, solar thermochemical water splitting, biological hydrogen production (cyanobacteria) (Velazquez Abad and Dodds 2017), and microbes that use light to make hydrogen (under research)(EIA 2020).

Table 6.7 Key performance and cost characteristics of different non-electric hydrogen production technologies (including CCS)

(1) CSIRO 2021; (2) IEA 2020; (3) IRENA 2019; (4) Hydrogen Council 2020; (5) CCC 2018; (6) BEIS 2021; (7) Ishaq et al. 2021; (8) Al-Mahtani et al. 2021; (9) IEA 2019

Technology	LHV Efficiency (%)		Carbon Intensity (kg_{CO2} $(kg_{H2})^{-1}$)	Cost Estimates* (USD $(kg_{H2})^{-1}$)	
	Current	Long-term		Current	Long-term
SMR	65[5]	74[5,6]	1.0–3.6[5,9]	1.0–2.7[1,2,3,4,5]	1.5–2.6[5]
Advanced gas reforming	-	81–84[5,6]	0.9–2.9[5]	1.3–2.1[5]	1.2–3.4[5,6]
Hydrogen from coal gasification	54[5]	54[5]	2.1–5.5[5,9]	1.8–3.1[1,2,3,4,5]	2.4–3.3[5]
Hydrogen from biomass gasification	53.6[7]	40–60[5]	Potential to achieve-Negative emission[5,8]	4.9[5]	2.9–5.9[5,6]

*USD per GBP exchange rate: 0.72 (August 2021); LHV: Lower Heating Values; Long-term refers to 2040 and 2050 according to different references

Table 6.8 Efficiency and cost characteristics of electrolysis technologies for hydrogen production

(1) CSIRO 2021; (2) IEA 2020; (3) IRENA 2019; (4) Hydrogen Council 2020; (5) CCC 2018; (6) BEIS 2021; (7) IEA 2019; (8) Christensen 2020

Technology	LHV Efficiency (%)		CAPEX (USD kW_e^{-1})		Cost Estimates*,+ (USD $(kg_{H2})^{-1}$)	
	Current	Long-term (2,5,6,8)	Current (7)	Long-term (7)	Current	Long-term
Alkaline Electrolysers	58–77[1,2,5,6,8]	70–82	500–1400	200–700	2.3–6.9[1,2,3,5]	0.9–3.9[3,5]
PEM	54–72[1,2,5,6,8]	67–82	1100–1800	200–900	3.5–9.3[1,4,5,6]	2.2–7.2[5,6]
SOEC	74–81[2,6,8]	77–92	2800–5600	500–1000	4.2[5]	2.6–3.6[5]

*USD per GBP exchange rate: 0.72 (August 2021); + The cost of hydrogen production from electrolysers is highly dependent on the technology, source of electricity, and operating hours, and here some values based on the assumptions made in the references are provided.

Hydrogen energy carriers. Hydrogen can be both an energy carrier itself, be converted further for into other energy carriers (such as synthetic fuels) and be a means of transporting other sources of energy. For example, hydrogen could be transported in its native gaseous form or liquified. Hydrogen can also be combined with carbon and transported as a synthetic hydrocarbons (Gumber and Gurumoorthy 2018) (IRENA 2019d) as well as be transported via liquid organic hydrogen carriers (LOHCs) or ammonia (IRENA 2019d). For synthetic hydrocarbons such as methane or methanol to be considered zero carbon, the CO_2 used to produce them would need to come from the atmosphere either directly through DACCS or indirectly through BECCS (IRENA 2019b). LOHCs are organic substances in liquid or semi-solid states, which store hydrogen based on reversible catalytic hydrogenation and de-hydrogenation of carbon double bounds (Rao and Yoon 2020; Niermann et al. 2019). Hydrogen produced from electrolysis could also be seen as an electricity energy carrier. This is an example of the PtX processes (section 6.4.4), entailing the conversion of electricity to other energy carriers for subsequent use.

Ammonia is a promising cost-effective hydrogen carrier (Creutzig et al. 2019). Onsite generation of hydrogen for the production of ammonia already occurs today, and the NH_3 could be subsequently "cracked" (with a 15–25% energy loss) to reproduce hydrogen (Bell and Torrente-Murciano 2016; Hansgen et al. 2010; Montoya et al. 2015). Because the energy density of ammonia is 38% higher than liquid hydrogen (Osman and Sgouridis 2018), it is potentially a suitable energy carrier for long-distance transport and storage (Salmon et al. 2021) Moreover, ammonia is more easily condensable (liquefied at 0.8 MPa, 20°C), which provides economically viable hydrogen storage and supply systems. Ammonia production and transport are also established industrial processes (~180 MMT yr^{-1} (Valera-Medina et al. 2017), and hence ammonia is considered to be a scalable and cost-effective hydrogen-based energy carrier. At present, most ammonia is used in fertilizers (~80%), followed by many industrial processes, such as the manufacturing of mining explosives and petrochemicals (Jiao and Xu 2018). In contrast to hydrogen, ammonia can be used directly as a fuel without any phase change for internal combustion engines, gas turbines, and industrial furnaces (Kobayashi et al. 2019). Ammonia can also be used in low and high temperature fuel cells (Lan and Tao 2014), whereby both electricity and hydrogen can be produced without any NOx emissions. Furthermore, ammonia provides the flexibility to be dehydrogenated for hydrogen-use purposes. Ammonia is considered a carbon-free sustainable fuel for electricity generation, since in a complete combustion, only water and nitrogen are produced (Valera-Medina et al. 2017). Like hydrogen, ammonia could facilitate management of variable RES, due to its cost-effective grid-scale energy storage capabilities. In this regard, production of ammonia via hydrogen from low- or zero-carbon generation technologies along with ammonia energy recovery technologies (Afif et al. 2016) could play a major role in forming a hydrogen and/or ammonia economy to support decarbonization. However, there are serious concerns regarding the ability to safely use ammonia for all these purposes, given its toxicity - whereas hydrogen is not considered toxic.

In general, challenges around hydrogen-based energy carriers - including safety issues around flammability, toxicity, storage, and consumption - require new devices and techniques to facilitate their large-scale use. Relatively high capital costs and large electricity requirements are also challenges for technologies that produce hydrogen energy carriers. Yet, these energy carriers could become economically viable through the availability of low-cost electricity generation and excess of renewable energy production (Daiyan et al. 2020) A key challenge in use of ammonia is related to significant amount of NO_x emissions, which is released from nitrogen and oxygen combustion, and unburned ammonia. Both have substantial air pollution risks, which can result in lung and other injuries, and can reduce visibility (EPA 2001). Due to the low flammability of hydrogen energy carriers such as liquified hydrogen (Nilsson et al. 2016) and ammonia (Li et al. 2018), a stable combustion (Zengel et al. 2020; Lamas and Rodriguez 2019) in the existing gas turbines is not currently feasible. In recent developments, however, the proportion of hydrogen in gas turbines has been successfully increased, and further development of gas turbines may enable them to operate on 100% hydrogen by 2030 (Pflug et al. 2019)

Long-Distance Hydrogen Transport. Hydrogen can allow regional integration and better utilization of low- or zero-carbon energy sources (Box 6.9 and Box 6.10). Hydrogen produced from renewables or other low-carbon sources in one location could be transported for use elsewhere (Philibert 2017; Ameli et al. 2020). Depending on the distance to the user and specific energy carrier utilized (e.g., gaseous hydrogen or LOHC), various hydrogen transport infrastructures, distribution systems, and storage facilities would be required (Hansen 2020; Schönauer and Glanz 2021) (Figure 6.17).

Hydrogen can be liquefied and transported at volume over the ocean without pressurization. This requires a temperature of –253ºC and is therefore energy-intensive and costly (Niermann et al. 2021). Once it reaches its destination, the hydrogen needs to be re-gasified, adding further cost. A demonstration project is under development exporting liquid hydrogen from Australia to Japan (Yamashita et al. 2019). Hydrogen could also be transported as ammonia by ocean in liquid form. Ammonia is advantageous because it is easier to store than hydrogen (Zamfirescu and Dincer 2008; Nam et al. 2018; Soloveichik 2016). Liquid ammonia requires temperatures below –33ºC and is therefore more straightforward and less costly to transport than liquified hydrogen and even liquified natural gas (Singh and Sahu 2018). A project exporting ammonia from Saudi Arabia to Japan is under consideration (Nagashima 2018). LOHCs could also be used to transport hydrogen at ambient temperature and pressure. This advantageous property of LOHCs makes them similar to oil products, meaning they can be transported in existing oil infrastructure including oil tankers and tanks (Niermann et al. 2019; IEA 2019). A project is under development to export hydrogen from Brunei to Japan using LOHCs (Kurosaki 2018).

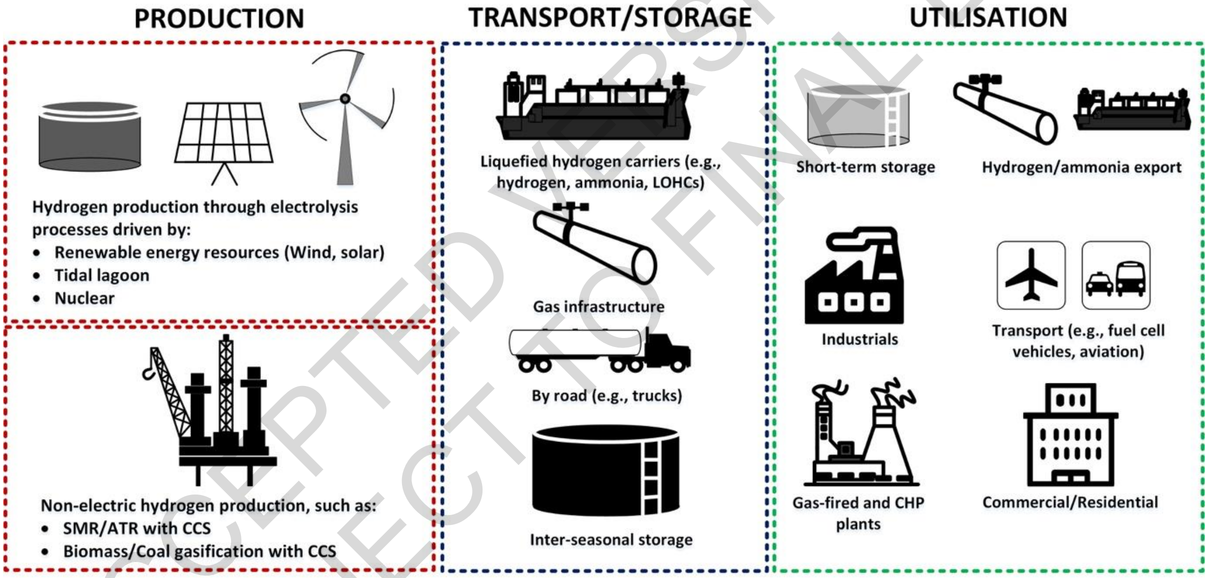


Figure 6.17 Hydrogen value chain. Hydrogen can be produced by various means and input and fuel sources. These processes have different emissions implications. Hydrogen can be transported by various means and in various forms, and it can be stored in bulk for longer-term use. It also has multiple potential end uses. CHP: Combined heat and power

Intra-Regional Hydrogen Transportation. Within a country or region, hydrogen would likely be pressurized and delivered as compressed gas. About three times as much compressed hydrogen by volume is required to supply the same amount of energy as natural gas. Security of supply is therefore more challenging in hydrogen networks than in natural gas networks. Storing hydrogen in pipelines (linepack) would be important to maintaining security of supply (Ameli et al. 2019, 2017). Due to the physics of hydrogen, in most cases exiting gas infrastructure would need to be upgraded to transport hydrogen. Transporting hydrogen in medium- or high-pressure networks most often would require reinforcements in compressor stations and pipeline construction routes (Dohi et al. 2016). There are several recent examples of efforts to transport hydrogen by pipeline. For example, in the Iron Mains Replacement Programme in the UK, the existing low pressure gas distribution pipes are being converted from iron to plastic (Committee on Climate Change 2018). In the Netherlands, an existing low-pressure 12 km natural gas pipeline has been used for transporting hydrogen (Dohi et al. 2016).

To bypass gas infrastructure in transporting hydrogen, methane can be transported using the existing gas infrastructure, while hydrogen can be produced close to the demand centres. This approach will only make sense if the methane is produced in a manner that captures carbon from the atmosphere and/or if CCS is used when the methane is used to produce hydrogen.

Bulk Hydrogen Storage. Currently, hydrogen is stored in bulk in chemical processes such as metal and chemical hydrides as well as in geologic caverns (Andersson and Grönkvist 2019; Caglayan et al. 2019) (e.g., salt caverns operate in Sweden) (Elberry et al. 2021). There are still many challenges, however, due to salt or hard rock geologies, large size, and minimum pressure requirements of the sites (IEA 2019c). Consequently, alternative carbon-free energy carriers, which store hydrogen, may become more attractive (Kobayashi et al. 2019; Lan et al. 2012).

6.4.5.2 Electricity Transmission

Given the significant geographical variations in the efficiency of renewable resources across different regions and continents, electricity transmission could facilitate cost effective deployment of renewable generation, enhance resilience and security of supply, and increase operational efficiency (*high confidence*). The diurnal and seasonal characteristics of different renewable energy sources such as wind, solar, and hydropower can vary significantly by location. Through enhanced electricity transmission infrastructure, more wind turbines can be deployed in areas with high wind potential and more solar panels in areas with larger solar irradiation. Increases in electricity transmission and trade can also enhance operational efficiency and reduce or defer the need for investment in peaking plants, storage, or other load management techniques needed to meet security of supply requirements associated with localized use of VRE sources. Increased interconnectivity of large-scale grids also allows the aggregation of 'smart grid' solutions such as flexible heating and cooling devices for flexible demand in industrial, commercial, and domestic sectors (Hakimi et al. 2020) and EVs (Li et al. 2021; Muratori and Mai 2020). In general, interconnection is more cost-optimal for countries that are geographically close to each other and can benefit from the diversity of their energy mixes and usage (Schlachtberger et al. 2017). Such developments are not without price, however, and amongst other concerns, raise issues surrounding land use, public acceptance, and resource acquisition for materials necessary for renewable developments (Vakulchuk et al. 2020; Capellán-Pérez et al. 2017).

A number of studies have demonstrated the cost benefits of interconnected grids in a range of geographical settings, including across the United States (Bloom et al. 2020), across Europe (2020; Newbery et al. 2013; Cluet et al. 2020), between Australia and parts of Asia (Halawa et al. 2018), and broader global regions, for example between the Middle East and Europe or North Africa and Europe (Tsoutsos et al. 2015). While there is growing interest in interconnection among different regions or continents, a broad range of geopolitical and socio-techno-economic challenges would need to be overcome to support this level of international co-operation and large-scale network expansion (Bertsch et al. 2017; Palle 2021).

Status of electricity transmission technology. Long-distance electricity transmission technologies are already available. High voltage alternating current (HVAC), high-voltage direct current (HVDC), and ultra HVDC (UHVDC) technologies are well-established and widely used for bulk electricity transmission (Alassi et al. 2019). HVDC is used with underground cables or long-distance overhead lines (typically voltages between 100–800 kV (Alassi et al. 2019) where HVAC is infeasible or not economic. A ~USD 17 bn project development agreement was signed in January 2021 that would connect 10 GW of PVs in the north of Australia via a 4500 km 3 GW HVDC cable to Singapore, suggesting that this would be cost effective (Sun Cable 2021). In September 2019, the Changji-Guquan ±1,100 kV ultra-high voltage direct current (UHVDC) transmission project built by State Grid

Corporation of China was officially completed and put into operation. The transmission line is able to transmit up to 12 GW over 3341 km (Pei et al. 2020). This is the UHVDC transmission project with the highest voltage level, the largest transmission capacity, and the longest transmission distance in the world (Liu 2015).

Other technologies that could expand the size of transmission corridors and/or improve the operational characteristics include low-frequency AC transmission (LFAC) (Xiang et al. 2021; Tang et al. 2021b) and half-wave AC transmission (HWACT) (Song et al. 2018; Xu et al. 2019). LFAC is technically feasible, but the circumstances in which it is the best economic choice compared to HVDC or HVAC still needs to be established (Xiang et al. 2016). HWACT is restricted to very long distances, and it has not been demonstrated in practice, so its feasibility is unproven. There are still a number of technological challenges for long-distance transmission networks such as protection systems for DC or hybrid AC-DC networks (Franck C. et al. 2017; Chaffey 2016), improvement in cabling technology, and including the use of superconductors and nanocomposites (Ballarino et al. 2016; Doukas 2019), which require advanced solutions.

Challenges, barriers, and recommendations. The main challenge to inter-regional transmission is the absence of appropriate market designs and regulatory and policy frameworks. In addition, there are commercial barriers for further enhancement of cross-border transmission. The differing impacts of cross-border interconnections on costs and revenues for generation companies in different regions could delay the development of these interconnectors. It is not yet clear how the investment cost of interconnections should be allocated and recovered, although there is growing support for allocating costs in accordance with the benefits delivered to the market participants. Increased cross-border interconnection may also require new business models which provide incentives for investment and efficient operation, manage risks and uncertainties, and facilitate coordinated planning and governance (Poudineh and Rubino 2017).

Optimizing the design and operation of the interconnected transmission system, both onshore and offshore grids, also requires more integrated economic and reliability approaches (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.

A wide range of factors, including generation profiles, demand profiles circuit losses, reliability characteristics, and maintenance, as well as the uncertainties around them will need to be considered in designing and operating long-distance transmission systems if they are to be widely deployed (De Sa and Al Zubaidy 2011; Du 2009; Djapic et al. 2008; E3G 2021). Public support for extending transmission systems will also be crucial, and studies indicate that such support is frequently low (Perlaviciute et al. 2018; Vince 2010).

6.4.6 Demand Side Mitigation Options from an Energy Systems Perspective

Demand-side measures are fundamental to an integrated approach to low carbon energy systems *(high confidence)*. Mitigation options, such as wind parks, CCS, and nuclear power plants, may not be implemented when actors oppose these options. Further, end users, including consumers, governments, businesses and industry, would need to adopt the relevant options, and then use these as intended; user adoption can be a key driver to scale up markets for low carbon technologies. This section discusses which factors shape the likelihood that end users engage in relevant mitigation actions, focusing on consumers; strategies to promote mitigation actions are discussed in Section 6.7.6.1.

A wide range of actions of end users 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), including:

- use of low carbon energy sources and carriers. Actors can produce and use their own renewable energy (e.g., install solar PV, solar water heaters, heat pumps), buy shares in a renewable energy project (e.g., wind shares), or select a renewable energy provider.

- adoption of technologies that support flexibility in energy use and sector coupling, thereby providing flexibility services by balancing demand and renewable energy supply. This would reduce the need to use fossil fuels to meet demand when renewable energy production is low and put less pressure on deployment of low-emission energy supply systems. Examples are technologies to store energy (e.g., batteries and electric vehicles) or that automatically shift appliances on or off (e.g., fridges, washing machines).
- adoption of energy-efficient appliances and systems and increase of resource efficiency of end uses so that less energy is required to provide the same service. Examples are insulating buildings, and passive or energy positive buildings.
- change behaviour to reduce overall energy demand or to match energy demand to available energy supplies. Examples include adjusting indoor temperature settings, reducing showering time, reducing car use or flying, and operating appliances when renewable energy production is high.
- purchase and use products and services that are associated with low GHG emissions during their production (e.g., reduce dairy and meat consumption) or for transporting products (e.g., local products). Also, end users can engage in 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 new products are used.

Various factors shape whether such mitigation actions are feasible and considered by end users, including contextual factors, individual abilities, and motivational factors. Mitigation actions can be facilitated and encouraged by targeting relevant barriers and enablers (section 6.7.6.2).

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

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

Motivation to engage in mitigation action, reflecting individuals' reasons for actions, depends on general goals that people strive for in their life (i.e., values). People who strongly value protecting the environment and other people are more likely to consider climate impacts and to engage in a wide range of mitigation actions than those who strongly value individual consequences of actions, such as pleasure and money (Taylor et al. 2014; Steg 2016). Values affect which types of costs and benefits people consider and prioritize when making choices, including individual, affective, social, and environmental costs and benefits (Gowdy 2008; Steg 2016).

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

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

Second, people are less likely to engage in mitigation behaviours that are unpleasurable or inconvenient (Steg 2016), and more likely to do so when they expect to derive positive feelings from such actions (Smith et al. 1994; Pelletier et al. 1998; Steg 2005; Carrus et al. 2008; Brosch et al. 2014; Taufik et al. 2016). Positive feelings may be elicited when behaviour is pleasurable, but also when it is perceived as meaningful (Bolderdijk et al. 2013; Taufik et al. 2015).

Third, 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 (Rai et al. 2016; Harland et al. 1999; Nolan et al. 2008). Being part of a group that advocates mitigation actions encourages such actions (Biddau et al. 2016; Fielding and Hornsey 2016; Jans et al. 2018). Talking with peers can reduce uncertainties and confirm benefits about adoption of renewable energy technology (Palm 2017), and peers can provide social support (Wolske et al. 2017). People may engage in mitigation actions when they think this would signal something positive about them (Griskevicius et al. 2010; Milinski et al. 2006; Kastner and Stern 2015; Noppers et al. 2014). Social influence can also originate from political and business leaders (Bouman and Steg 2019); GHG emissions are lower when legislators have strong environmental records (Jensen and Spoon 2011; Dietz et al. 2015).

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

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

6.4.7 Summary of Mitigation Options

Designing feasible, desirable, and cost-effective energy sector mitigation strategies requires comparison between the different mitigation options. One such metric is the cost of delivering one unit of energy, for example, the levelized cost, or USD MWh^{-1}, of electricity produced from different sources. LCOEs are useful because they normalize the costs per unit of service provided. While useful in characterizing options in broad strokes, it is important to acknowledge and understand several caveats associated with these metrics, particularly when applied globally. They may be constructed with different discount rates; they require information on energy input costs for options that require energy inputs (e.g., fossil electricity generation, biofuels); they depend on local resource availability, for example solar insolation for solar power, wind classes for wind power, and rainfall and streamflow for hydropower; and actual implementation costs may include additional elements, for example, the costs of managing electricity grids heavily dependent on VRE electricity sources. These complicating factors vary across regions, some depend strongly on the policy environment in which mitigation options are deployed, and some depend on how technologies are constructed and operated.

The literature provides multiple LCOE estimates for mitigation options today and in the future (see Table 6.9 for electricity generation options). LCOE ranges for low- and zero-carbon electricity technologies overlap with LCOE's of fossil generation without CCS. For example, LCOEs for utility solar and wind today and in the future overlap with those of new coal and gas without CCS (Figure 6.18, NREL 2021; Lazard, 2020; IEA WEO 2020, IEA WEO 2020). Some of the overlap stems from differences in assumptions or regional conditions that apply to all technologies (e.g., variations in assumed discount rates), but the overlap also reflects the fact that low- and zero-carbon electricity generation options are, and will be, less expensive than emitting options in many regions. Future cost projections also illustrate that several technologies are anticipated to experience further cost declines over the coming decades, reinforcing the increasingly competitiveness of low- and zero-carbon electricity. For example, IEA's LCOEs estimates for offshore wind halve between 2020 and 2040 in several regions (IEA WEO 2020).

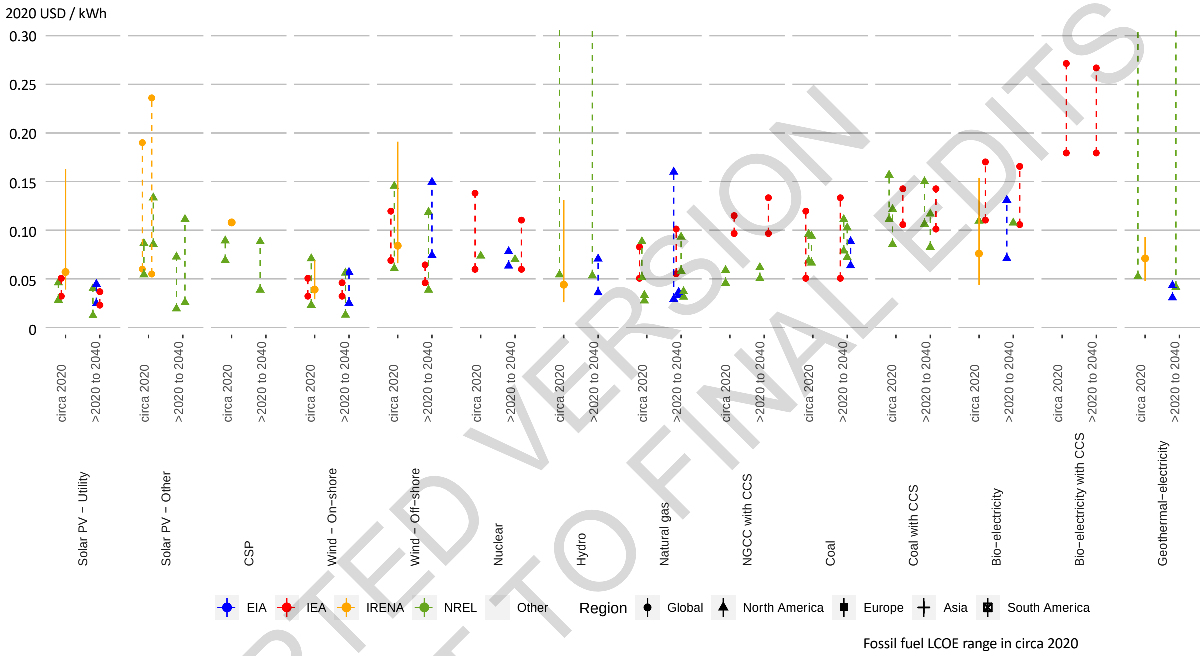


Figure 6.18 Range of LCOEs (in USD cents kWh^{-1}) from recent studies for different electricity generating technologies circa 2020 and in the future between 2020-2040. LCOEs are primarily taken from recent studies, because the costs of some technologies are changing rapidly. To make the figure more tractable across the studies, we highlight the data from IEA WEO 2020 STEPS scenario in red (EIA, 2020), the EIA AEO 2021 in blue (EIA, 2021), NREL ATB 2021 in green, (NREL, 2021), and IRENA Renewable Power Generation Costs in 2020 in yellow (IRENA, 2021). All other studies are shown in light grey markers. Marker shapes identify the regions included in the studies. Studies that included several regions are labelled as global. Only sources that provided LCOEs are included. Ranges for studies frequently reflect variations among regional estimates. Studies that are shown as a mid-point and a solid line represent studies that reported either a median or an average, and that had either a confidence interval or a minimum and a maximum reported. Dashed lines with markers at the end represent the range of values reported in studies that had several point estimates for either different regions or used different assumptions. All estimates were converted to 2020 USD. The publication year was used if no USD year was provided. Some studies included transmissions costs, and some the CCS studies included storage and sequestration costs, while others did not. Vertical axis is capped at USD$_{2020}$ 0.30 kWh^{-1}, but some estimates for hydro, geothermal, natural gas and bioelectricity were higher than 0.30. The grey horizontal band denotes the range of fossil fuel electricity LCOEs in circa 2020.

A more direct metric of mitigation options is the cost to reduce one tonne of CO_2 or equivalent GHGs, or USD tCO_2-eq^{-1} avoided. In addition to the comparison challenges noted above, this metric must account for the costs and emissions of the emitting options that is being displaced by the low-carbon option. Assumptions about the displaced option can lead to very different mitigation cost estimates

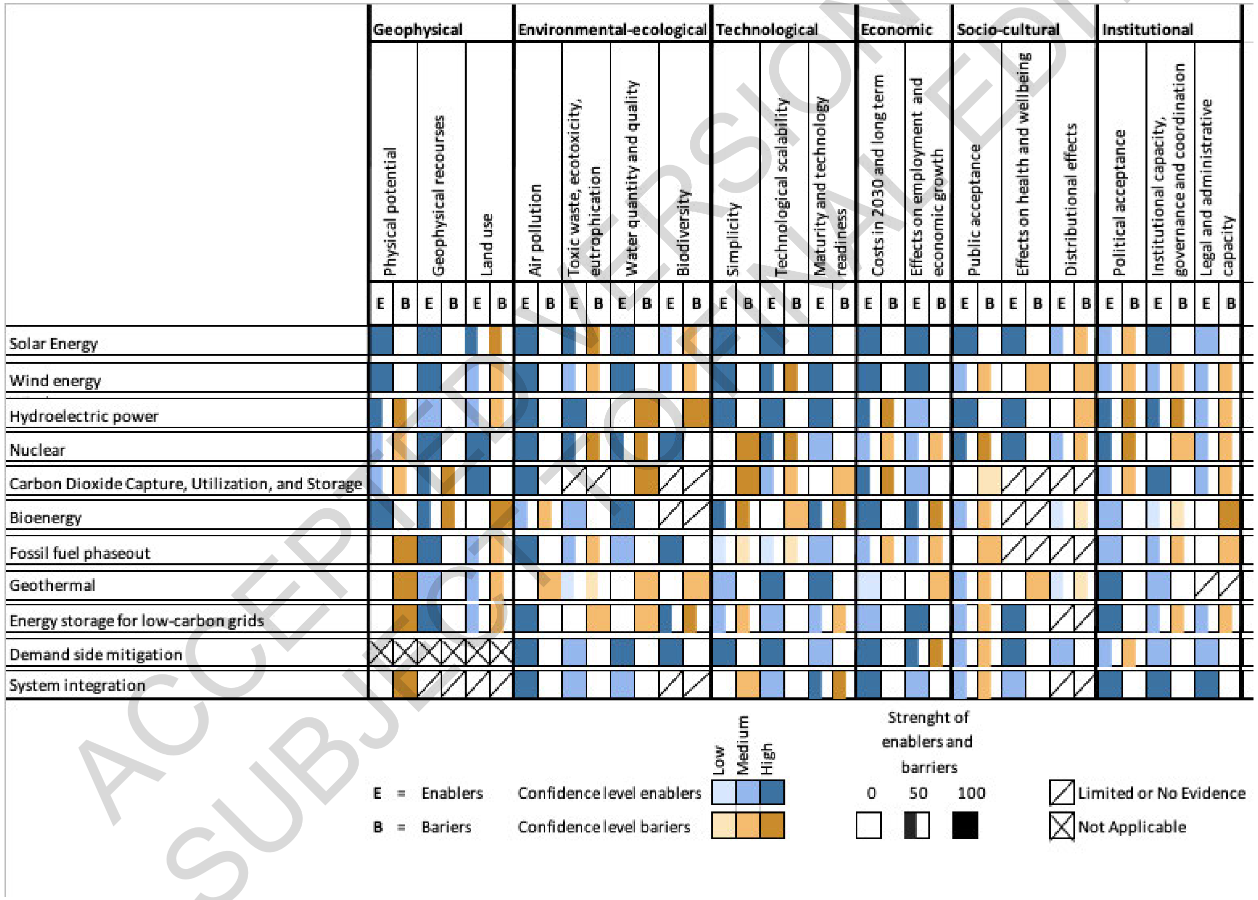
(Table 6.9). Despite these challenges, these metrics are useful for identifying broad trends and making broad comparisons, even from the global perspective in this assessment. But local information will always be critical to determine which options are most cost-effective in any specific applications.

Table 6.9 Examples of cost of mitigation for selected electricity options. Results represent variations in mitigation options and displaced fossil generation. LCOEs are illustrative, but consistent with recent estimates. Negative values mean that the mitigation option is cheaper than the displaced option, irrespective of emissions benefits.

		Baseline			
		New coal	Existing coal	New NGCC	Existing NGCC
	Baseline emissions rate (tonCO_2 MWh^{-1})	0.8	0.9	0.34	0.42
	LCOE (USD_{2020} kWh^{-1})	0.065	0.041	0.044	0.028
Utility scale solar PV (poor resource site)	0.100	44 USD tCO2-eq^{-1}	66 USD tCO2-eq^{-1}	165 USD tCO2-eq^{-1}	171 USD tCO2-eq^{-1}
Utility scale solar PV (good resource site)	0.035	–38 USD tCO2-eq^{-1}	–7 USD tCO2-eq^{-1}	–26 USD tCO2-eq^{-1}	17 USD tCO2-eq^{-1}

The feasibility and desirability of mitigation options extends well beyond the market economic costs of installation and operation (Section 6.4.1). Figure 6.19 summarizes the barriers and enablers for implementing different mitigation options in energy systems. The feasibility of different options can be enhanced by removing barriers and/or strengthening enablers of the implementation of the options. The feasibility of options may differ across context (e.g., region), time (e.g., 2030 versus 2050), scale (e.g., small versus large) and the long-term warming goal (e.g., 1.5°C versus 2°C).

Figure 6.19 Summary of the extent to which different factors would enable or inhibit the deployment of mitigation options in energy systems. Blue bars indicate the extent to which the indicator enables the implementation of the option (E) and orange bars indicate the extent to which an indicator is a barrier (B) to the deployment of the option, relative to the maximum possible barriers and enablers assessed. An X signifies the indicator is not applicable or does not affect the feasibility of the option, while a forward slash indicates that there is no or limited evidence whether the indicator affects the feasibility of the option. The shading indicates the level of confidence, with darker shading signifying higher levels of confidence. Appendix II provides an overview of the factors affecting the feasibility of options and how they differ across context (e.g., region), time (e.g., 2030 versus 2050), and scale (e.g., small versus large), and includes a line of sight on which the assessment is based. The assessment method is explained in Annex II.11.



6.5 Climate Change Impacts on the Energy System

6.5.1 Climate Impacts on the Energy System

Many components of the energy system are affected by individual weather events and climate conditions (Table 6.10). In addition, a range of compounding effects can be anticipated, as the complex, interconnected climate and energy system are influenced by multiple weather and climate conditions. This raises the question of whether the energy system transformation needed to limit warming will be impacted by climate change.

Table 6.10 Relevance of the key climatic impact-drivers (and their respective changes in intensity, frequency, duration, timing, and spatial extent) for major categories of activities in the energy sector. The climate impact-drivers (CIDs) are identified in AR6/GWI/Chapter 12 (ref). The relevance is assessed as: positive/negative (+ or –), or both (±). D&O: Design and Operation, CF: Capacity Factor.

		Climate Impact Driver																																
		Heat and cold				Wet and dry								Wind				Snow and ice						Coastal			Oceanic					Other		
Energy sector	Energy activity	Mean air temperature	Extreme heat	Cold spell	Frost	Mean precipitation	River flood	Heavy precipitation and pluvial flood	Landslide	Aridity	Hydrological drought	Agricultural and ecological drought	Fire weather	Mean wind speed	Severe wind storm	Tropical cyclone	Sand and dust storm	Snow, glacier and ice sheet	Permafrost	Lake, river and sea ice	Heavy snowfall and ice storm	Hail	Snow avalanche	Relative sea level	Coastal flood	Coastal erosion	Mean ocean temperature	Marine heatwave	Ocean acidity	Ocean salinity	Dissolved oxygen	Air pollution weather	Atmospheric CO2 at surface	Radiation at surface
Hydropower	Resources (dammed)					+	+			–	–	–						±		–														
	D&O (dammed)							±	–												–													
	Resources (undammed)					+	+	+			–	–																						
	D&O (undammed)							±	–									±		–	–													
Wind power	Capacity factors	–			–									+	–	–																		
	D&O (onshore)				–										–	–	–				–	–			–	–								
	D&O (offshore)														–	–						–		–										
Solar power	CF (PV)	–	–																													–		+
	CF (CSP)			–																												–		+
	D&O												–				–	–				–												
Ocean energy	Resources													+	±	+						–		±	±		–			±				
Bio-energy	Resources	±	–			±					–	–	–																				+	
Thermal power plants (incl nuclear)	Efficiency	±	–								–																							
	Vulnerability		–	–	–		–	–	–		–		–								–			–	–									
CCS	Efficiency	±								–	–	–																						
Energy consumption	Heating	+		–										–																				+
	Cooling	–	–											±																				–
Electric power transmission system	D&O	–	–										–																					
	Vulnerability		–										–		–	–					–		–											

The impacts of *climate change* on the energy system can be divided into three areas: impacts on the energy supply, impacts on energy consumption, and impacts on energy infrastructure. The rest of this section focuses on how the *future changes* in climate drivers might affect the ability of the energy system transformation needed to mitigate climate change. The discussion of energy infrastructure in this section is limited to electric electricity system vulnerability.

6.5.2 Impacts on Energy Supply

The increased weather-dependency of future low-carbon electricity systems amplifies the possible impacts of climate change (Staffell and Pfenninger 2018). However, *globally* climate change impacts on electricity generation – including hydro, wind and solar power potentials – should not compromise climate mitigation strategies (*high confidence*). Many of the changes in the climate system will be geographically complex at the regional and local levels. Thus, *regionally* climate change impacts on electricity generation could be significant. Climate change impacts on bioenergy potentials are more uncertain because of uncertainties associated with the crop response to climate change, future water availability and crop deployment. Climate change can reduce the efficiency of thermal power generation and increase the risk of power plant shutdowns during droughts. The potential additional cooling water needs of CCS can increase these risks.

6.5.2.1 Hydropower

The impacts of climate change on hydropower will vary by region. High latitudes in the northern hemisphere are anticipated to experience increased runoff and hydropower potential. For other regions, studies find both increasing and decreasing runoff and hydropower potential. Areas with decreased runoff are anticipated to experience reduced hydropower production and increased water conflict among different economic activities. (*high confidence*)

Hydropower production is directly related to the availability of water. Changes in runoff and its seasonality and changes in temperature and precipitation intensity will influence hydro electricity production (IHA 2019). In general, increased precipitation will increase water availability and hydropower production. Increased precipitation intensity, however, may impact the integrity of dam structures and affect power production by increasing debris accumulation and vegetation growth. Additionally, increased precipitation intensity results in the silting of the reservoirs or increases the amount of water spilt, resulting in erosion (Schaeffer et al. 2012; IHA 2019). Climate change will likely lead to higher air temperatures, resulting in more surface evaporation, less water storage, and loss of equipment efficiency (Ebinger and Vergara 2011; Fluixá-Sanmartín et al. 2018; Hock et al. 2019; Mukheibir 2013). Climate change may alter the demands for water use by other sectors that often rely on stored water in multi-purpose reservoirs and may therefore generate conflicts over water use. The increased need for water for irrigation and/or industry can affect the availability of water for hydropower generation (Solaun and Cerdá 2017; Spalding-Fecher et al. 2016). Higher temperatures increase glacier melt, increasing water availability for hydropower while the glaciers exist. Changes in the timing of snow and ice melt may require upgrading in storage capacity and adaptation of the hydropower plant management for fully exploiting the increase in water availability.

Global Solar Atlas (ESMAP 2019)

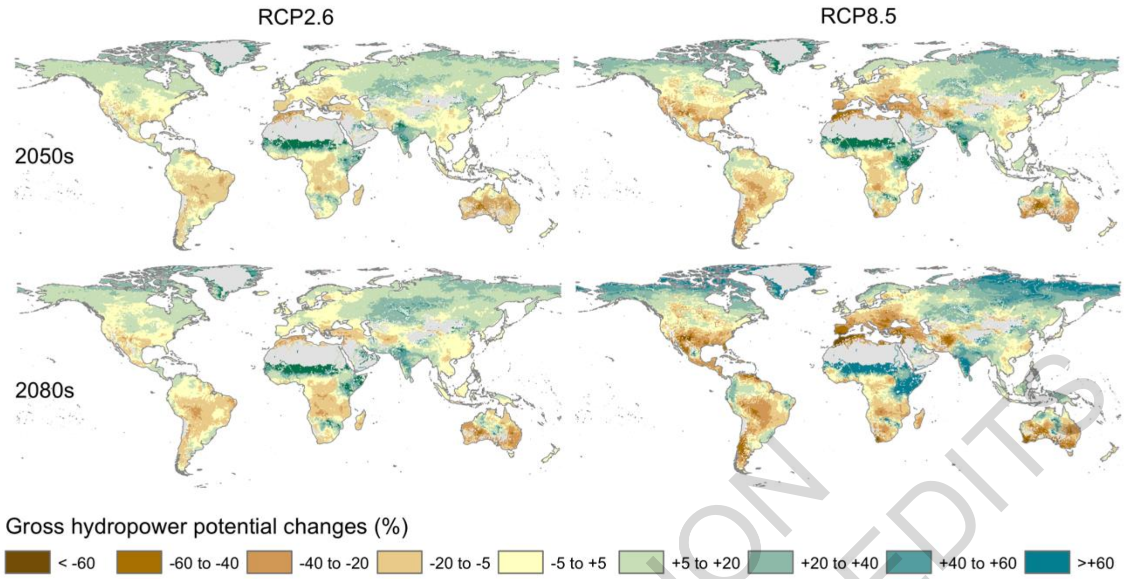


Figure 6.20 Global spatial patterns of changes in gross hydropower potential based on climate forcing from five climate models. Changes are shown for the 2050s (upper) and the 2080s (lower) for the low emission scenario (RCP2.6; left) and highest emission scenario (RCP8.5; right) scenarios relative to the control period (1971–2000). [Data source: (van Vliet et al. 2016a)].

The conclusions regarding climate change impacts on hydropower vary due to differences in modelling assumptions and methodology, such as choice of the climate and hydrological models, choice of metrics (e.g., projected production vs hydropower potential), level of modelling details between local and global studies, reservoir operation assumptions. Also important is how hydropower production matches up with other reservoir purposes, accounting for other water and energy users, and how the competing uses are impacted by climate change (Turner et al. 2017; van Vliet et al. 2016b). Nonetheless, analyses consistently demonstrate that the global impact of climate change on hydropower will be small, but the regional impacts will be larger, and will be both positive and negative (Figure 6.20) Gross global hydropower potential in the 2050s has been estimated to slightly decrease (Hamududu and Killingtveit 2012) between 0.4% (for the low emission scenario) and 6.1% (for the highest emission scenario) for the 2080s compared to 1971–2000 (van Vliet et al. 2016a).

Regional changes in hydropower are estimated from 5–20% increases for most areas in high latitudes (van Vliet et al. 2016b; Turner et al. 2017) to decreases of 5–20% in areas with increased drought conditions (Cronin et al. 2018). Models show a consistent increase in streamflow and hydropower production by 2080 in high latitudes of the northern hemisphere and parts of the tropics (Figure 6.20) (e.g., central Africa and southern Asia) while decreasing in the U.S., southern and central Europe, Southeast Asia and southern South America, Africa and Australia (van Vliet et al. 2016c,a). Decreases in hydropower production are indicated for parts of North America, central and southern Europe, the Middle East, central Asia and Southern South America. Studies disagree on the changes in hydropower production in China, central South America, and partially in southern Africa (Solaun and Cerdá 2019; Hamududu and Killingtveit 2012; van Vliet et al. 2016b; Fan et al. 2020).

6.5.2.2 Wind Energy

Climate change will not substantially impact future wind resources and will not compromise the ability of wind energy to support low-carbon transitions (*high confidence*). Changing wind variability may have a small to modest impact on backup energy and storage needs (*low confidence*); however, current evidence is largely from studies focused on Europe.

Long-term global wind energy resources are not expected to substantially change in future climate scenarios (Karnauskas et al. 2018; Yalew et al. 2020; Pryor et al. 2020). However, recent research has indicated consistent shifts in the geographic position of atmospheric jets in the high emission scenarios (Harvey et al. 2014), which would decrease wind power potentials across the Northern Hemisphere mid-latitudes and increase wind potentials across the tropics and the Southern Hemisphere. However, the climate models used to make these assessments differ in how well they can reproduce the historical wind resources and wind extremes, which raises questions about the robustness of their predictions of future wind resources (Pryor et al. 2020).

There are many regional studies on changes in wind resources from climate change. For Europe, there is medium evidence and moderate agreement that wind resources are already increasing and will continue to increase in Northern Europe and decrease in Southern Europe (Moemken et al. 2018; Carvalho et al. 2017; Devis et al. 2018). For North America, the various studies have low agreement for the changes in future wind resources in part because the year-to-year variations in wind resources are often larger than the future change due to climate change (Johnson and Erhardt 2016; Wang et al. 2020b; Costoya et al. 2020; Chen 2020). Studies show increases in future wind resources in windy areas in South America (Ruffato-Ferreira et al. 2017; de Jong et al. 2019). No robust future changes in wind resources have been identified in China (Xiong et al. 2019). However, none of the global or regional studies of the effects of climate change on wind resources considers the fine-scale dependence of wind resources on the topography and wind direction (Sanz Rodrigo et al. 2016; Dörenkämper et al. 2020) or the effect of expanding wind energy exploitation (Lundquist et al. 2019; Volker et al. 2017). There is limited evidence that extreme wind speeds, which can damage wind turbines, will increase due to climate change (Pes et al. 2017; Pryor et al. 2020). Nevertheless, projected changes in Europe and North America – regions where the most extensive analysis has been undertaken – are expected to be within the estimates embedded in the design standards of wind turbines (Pryor and Barthelmie 2013).

Future wind generation in Europe could decrease in summer and autumn, increasing in winter in northern-central Europe but decreasing in southernmost Europe (Carvalho et al. 2017). Towards 2100, intra-annual variations increase in most of Europe, except around the Mediterranean area (Reyers et al. 2016), but this may reflect natural multidecadal variability (Wohland et al. 2019b). Wind speeds may become more homogeneous over large geographical regions in Europe due to climate change, increasing the likelihood of large areas experiencing high or low wind speeds simultaneously (Wohland et al. 2017). These changes could result in fewer benefits in the transmission of wind generation between countries and increased system integration costs. Europe could require a modest increase (up to 7%) in backup energy towards the end of the 21st century due to more homogeneous wind conditions over Europe (Wohland et al. 2017; Weber et al. 2018). However, other studies report that impact of climate change is substantially smaller than interannual variability, with no significant impact on the occurrence of extreme low wind production events in Europe (Van Der Wiel et al. 2019). If European electricity systems are designed to manage the effects of existing weather variability on wind power, they can likely also cope with climate change impacts on wind power (Ravestein et al. 2018). Changes in wind generation variability caused by climate change are also reported for North America (Haupt et al. 2016; Losada Carreño et al. 2018), with modest impacts on electricity system operation (Craig et al. 2019).

6.5.2.3 Solar Energy

Climate change is not expected to substantially impact global solar insolation and will not compromise the ability of solar energy to support low-carbon transitions (*high confidence*). Models show dimming and brightening in certain regions, driven by cloud, aerosol and water vapour trends [WGI,ch12,p31]. The increase in surface temperature, which affects all regions, decreases solar power output by reducing the PV panel efficiency. In some models and climate scenarios, the increases in solar insolation are counterbalanced by reducing efficiency due to rising surface air temperatures, which increase significantly in all models and scenarios (Jerez et al. 2015; Bartók et al. 2017; Emodi et al. 2019). Increases in aerosols would reduce the solar resource available and add to maintenance costs [AR6,WGI,ch12].

In many emission scenarios, the effect on solar PV from temperature-induced efficiency losses is smaller than the effect expected from changes on solar insolation due to variations in water vapour and clouds in most regions. Also, future PV technologies will likely have higher efficiency, which would offset temperature-related declines (Müller et al. 2019). Cloud cover is projected to decrease in the subtropics (around –0.05% per year), including parts of North America, vast parts of Europe and China, South America, South Africa and Australia (medium agreement, medium evidence). Thus, models project modest (< 3%) increases in solar PV by the end of the century for southern Europe, northern and southern Africa, Central America, and the Caribbean (Emodi et al. 2019). There are several studies projecting decreasing solar production, but these are generally influenced by other factors, for example, increasing air pollution (Ruosteenoja et al. 2019). The multi-model means for solar insolation in regional models decrease 0.60 W m^{-2} per decade from 2006 to 2100 over most of Europe (Bartók et al. 2017), with the most significant decreases in the Northern countries (Jerez et al. 2015).

6.5.2.4 Bioenergy

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

Climate change will shift the suitable range for bioenergy towards higher latitudes, but the net change in the total suitable area is uncertain (*high confidence*). Several studies show northward shifts in the suitable range for bioenergy in the northern hemisphere (Tuck et al. 2006; Bellarby et al. 2010; Preston et al. 2016; Barney and DiTomaso 2010; Hager et al. 2014; Conant et al. 2018; Cronin et al. 2018; Wang et al. 2014a), but the net effect of climate change on total suitable area varies by region, species, and climate model (Barney and DiTomaso 2010; Hager et al. 2014; Wang et al. 2014a).

The effect of climate change on bioenergy crop yields will vary across region and feedstock (*high confidence*); however, in general, yields will decline in low latitudes (*medium confidence*) and increase in high latitudes (*low confidence*) (Haberl et al. 2010; Cosentino et al. 2012; Mbow et al. 2019; Cronin et al. 2018; Preston et al. 2016). However, the average change in yield varies significantly across studies, depending on the feedstock, region, and other factors (Dolan et al. 2020; Kyle et al. 2014) Mbow et al. (2019); Beringer et al. (2011). Only a few studies extend the modelling of climate change impacts on bioenergy to quantify the effect on bioenergy deployment or its implications on the energy system (Calvin et al. 2013, 2019; Thornton et al. 2017; Kyle et al. 2014). These studies find that changes in deployment are of the same sign as changes in yield; that is, if yields increase, then deployment increases.

Some of the uncertainty in the sign and magnitude of the impacts of climate change on bioenergy potential is due to uncertainties in CO_2 fertilization (the increase in photosynthesis due to increases in atmospheric CO_2 concentration) (Bonjean Stanton et al. 2016; Haberl et al. 2011; Cronin et al. 2018; Solaun and Cerdá 2019; Yalew et al. 2020). For example, earlier studies found that without CO_2

fertilization, climate change will reduce global bioenergy potential by about 16%; with CO_2 fertilization, however, climate change increases this potential by 45% (Haberl et al. 2011). However, newer studies in the U.S. find little effect of CO_2 fertilization on switchgrass yield (Dolan et al. 2020). There is also a considerable uncertainty across climate and crop models in estimating bioenergy potential (Hager et al. 2014).

6.5.2.5 Thermal power plants

The operation of thermal power plants will be affected by climate change, deriving from changes in the ambient conditions like temperature, humidity and water availability (Schaeffer et al. 2012) (*high confidence*). Changes in ambient temperature have relatively small impacts on coal-fired and nuclear power plants (Rankine cycle); however, gas-fired power plants (Brayton or combined-cycle) may have their thermal efficiency and power output significantly decreased (De Sa and Al Zubaidy 2011; Schaeffer et al. 2012). Droughts decrease potential cooling water for thermal power plants and increase the probability of water outlet temperatures exceeding regulatory limits, leading to lower production or even shutdowns. Thermal power utilization has been reported to be on average 3.8% lower during drought years globally (van Vliet et al. 2016c). and further significant decreases in available thermal power plant capacity due to climate change are projected (Koch et al. 2014; van Vliet et al. 2016b; Yalew et al. 2020) . An increase in climate-related nuclear power disruptions has been reported in the past decades globally (Ahmad 2021).

Carbon capture may increase cooling water usage significantly, especially in retrofits, with up to 50% increase in water usage for coal-fired power plants globally, depending on the CCS technology (Rosa et al. 2020, Section 6.4). In Asia, planned coal capacity is expected to be vulnerable to droughts, sea level rise, and rising air temperatures, and this may be exacerbated by incorporating carbon capture (Wang et al. 2019c). Recently, however, studies have proposed designs of CCS with a minimal increase in water requirements (Mikunda et al. 2021; Magneschi et al. 2017).

Older thermal power plants can be retrofitted to mitigate climate impacts by altering and redesigning the cooling systems (Westlén 2018), although the costs for these solutions may be high. For example, dry cooling may be used instead of once-through cooling; however, it lowers thermal efficiency and would leave plants vulnerable to ambient temperature increase (Ahmad 2021). Closed-circuit cooling is much less sensitive to water temperature than once-through cooling (Bonjean Stanton et al. 2016). Modifying policies and regulation of water and heat emissions from power plants may also be used to mitigate plant reliability problems induced by climate change (Eisenack 2016; Mu et al. 2020), albeit with potential impacts for other water users and ecology. Improvements in water use and thermal efficiencies and the use of transmission capabilities over large geographical regions to mitigate risks on individual plants are also possible mitigation options (Miara et al. 2017).

6.5.3 Impacts on Energy Consumption

Heating demand will decrease, and cooling demand will increase in response to climate change. Peak load may increase more than energy consumption, and the changing spatial and temporal load patterns can impact transmission and needs for storage, demands-side management, and peak-generating capacity. (*high confidence*)

Climate change will decrease heating demands, especially in cold regions, and it will increase cooling demands, especially in warm regions (Yalew et al. 2020). Recent studies report significant net impacts, with the commercial and industrial sectors and substantial air condition penetration driving an increase in energy demand (De Cian and Sue Wing 2019; Levesque et al. 2018; van Ruijven et al. 2019; Davis and Gertler 2015; Yalew et al. 2020). For example, globally, De Cian and Sue Wing (2019) found a 7–17% increase in energy consumption due to climate change in 2050, with the range depending on the climate change scenario. The overall effects of climate change on building energy consumption are regionally dependent. For example, Zhang et al. (2019) find that reduced heating will outweigh increased cooling in the residential buildings in Europe, but the reverse will be true in China.

While many studies have focused on energy consumption, climate extremes are expected to alter peak energy demands, with the potential for blackouts, brownouts, and other short-term energy system impacts (Yalew et al. 2020). For example, peak energy demand during heatwaves can coincide with reduced transmission and distribution capacity at higher temperatures. In large cities, extreme heat events increase cooling degree days significantly, with the urban heat island effect compounding the impact (Morakinyo et al. 2019). One study found that total electricity consumption at the end of the century in the U.S. could increase on average by 20% during summer months and decrease on average by 6% in the winder (Ralston Fonseca et al. 2019). While the average increase in consumption is modest, climate change is projected to have severe impacts on the frequency and intensity of peak electricity loads. (Auffhammer et al. 2017). Bartos et al. (2016) find that peak per-capita summertime load in the U.S. may rise by 4.2%–15% by mid-century. Efficient cooling technologies and other demand side measures can limit cooling energy loads during periods of particularly high demand(Dreyfus et al. 2020; International Energy Agency (IEA) 2018).

[START BOX 6.6 HERE]

Box 6.6 Energy Resilience

In February 2021, the state of Texas was hit by three major storms and suffered significant scale power outages. More than 4.5 million homes and businesses on the Texas electric grid were left without electricity for days, limiting the ability to heat homes during dangerously low temperatures and leading to food and clean water shortages (Busby et al. 2021). The Texas and other events – e.g., during Typhoon Haiyan that affected Southeast Asia in 2013; the Australian bush fires in 2019–2020 and forest fires in 2018 in California; water shortages in Cape Town, South Africa in 2018 and the western United States during 2021 – raise the question of whether future low-carbon energy systems will be more or less resilient than those of today.

Some characteristics of low-carbon energy systems will make them less resilient. Droughts reduce hydroelectric electricity generation (Gleick 2016; van Vliet et al. 2016c); wind farms do not produce electricity in calm conditions or shut down in very strong winds (Petersen and Troen 2012); solar PV generation is reduced by clouds and is less efficient under extreme heat, dust storms, and wildfires (Perry and Troccoli 2015; Jackson and Gunda 2021). In addition, the electrification of heating will increase the weather dependence of electricity consumption (Staffell and Pfenninger 2018; Gea-Bermúdez et al. 2021). Non-renewable generation, for example from nuclear and fossil power plants, are also vulnerable to high temperatures and droughts as they depend on water for cooling (Cronin et al. 2018; Ahmad 2021).

But some aspects of low-carbon energy systems will make them more resilient. Wind and solar farms are often spread geographically, which reduces the chances of being affected by the same extreme weather event (Perera et al. 2020). The diversification of energy sources, in which each component has different vulnerabilities, increases resilience. Less reliance on thermal electricity generation technologies will reduce the risks of curtailment or efficiency losses from droughts and heat waves. (Lohrmann et al. 2019). More generally, increased electricity system integration and flexibility (Section 6.4.3) and weatherization of generators increases electricity system resilience (Heffron et al. 2021; Busby et al. 2021). Likewise, local district micro-grids with appropriate enabling technologies (e.g., distributed generation, energy storage, greater demand-side participation, electric vehicles) may ensure access to electricity during major long-duration power outage events and radically enhance the resilience of supply of essential demand (Stout et al. 2019).

[END BOX 6.6 HERE]

6.5.4 Impacts on Electricity 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 significant economic losses along with cascading impacts on health and safety. Extreme weather and storms threaten the electricity system in different ways, affecting system resilience, reliability, and adequacy (Moreno-Mateos et al. 2020). The implications of climate change for electricity system vulnerability will depend on the degree to which climate change alters the frequency and intensity of extreme weather events. The complex compounding effects of simultaneous events (e.g., high winds and lightning occurring at the same time) are not well understood.

High wind speeds can shear lines through mechanical failure or cause lines to collide, causing transient events (Panteli and Mancarella 2015; Yalew et al. 2020). Hurricane conditions can damage electricity system infrastructures, including utility-scale wind and solar PV plants. Electricity systems may experience high demand when lines are particularly at risk from mechanical failure from wind and storm-related effects. However, except for medium evidence of increases in heavy precipitation associated with tropical cyclones, there is limited evidence that extreme wind events will increase in frequency or intensity in the future (Kumar et al. 2015; Pryor et al. 2020).

Wildfires pose a significant threat to electricity systems in dry conditions and arid regions (Dian et al. 2019). With climate change, wildfires will probably become more frequent (Flannigan et al. 2013) and more difficult to address given that they frequently coincide with dry air and can be exacerbated by high winds (Mitchell 2013).

Lightning can cause wildfires or common-mode faults on electricity systems associated with vegetation falling on power substations or overhead lines but is more generally associated with flashovers and overloads (Balijepalli et al. 2005). Climate change may change the probability of lightning-related events (Romps et al. 2014).

Snow and icing can impact overhead power lines by weighing them down 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 (Croce et al. 2018; Yaji et al. 2014) and snow and ice can impact wind turbines (Davis et al. 2016). Climate change will lower risk of snow and ice conditions (McColl et al. 2012), but there is still an underlying risk of sporadic acute cold conditions such as those associated with winter storms in Texas in 2021 (Box 6.).

Flooding poses a threat to the transmission and distribution systems by inundating low-lying substations and underground cables. Coastal flooding also poses a threat to electricity system infrastructure. Rising sea levels from climate change and associated storm surge may also pose a significant risk for coastal electricity systems (Entriken and Lordan 2012).

Temperature increases influence electricity load profiles and electricity generation, as well as potentially impact supporting information and communication infrastructure. Heat can pose direct impacts to electricity system equipment such as transformers. Referred to as solar heat faults, they occur under high temperatures and low wind speeds and can be exacerbated by the urban heat island effect (McColl et al. 2012). Increasing temperatures affect system adequacy by reducing electric transmission capacity, simultaneously increasing peak load due to increased air conditioning needs (Bartos et al. 2016).

[START BOX 6.7 HERE]

Box 6.7 Impacts of Renewable Energy Production on Climate

While climate change will affect energy systems (Section 6.5), the reverse is potentially also true: increasing the use of renewable energy sources could affect local climate. Large solar PV arrays and hydroelectric dams darken the land surface, and wind turbines extract the wind's kinetic energy near the Earth's surface. Their environmental impacts of renewable energy production are mostly confined to areas close to the production sources and have shown to be trivial compared to the mitigation benefits of renewable energy (*high confidence*).

Solar Energy. Observations and model simulations have addressed whether large-scale solar PV power plants can alter the local and regional climate. In rural areas at the local scale, large-scale solar PV farms change the surface characteristics and affect air temperatures (Taha 2013). Measurements in rural Arizona, U.S. show local nighttime temperatures 3–4°C warmer at the PV farm than surroundings (Barron-Gafford et al. 2016). In contrast, measurements in urban settings show that solar PV panels on roofs provide a cooling effect (Ma et al. 2017; Taha 2013). On the regional scale, modelling studies suggest 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 show that solar panels induce regional cooling by converting part of the incoming solar energy to electricity (Hu et al. 2016). However, converting the generated electricity to heat in urban areas increases regional and local temperatures, compensating for the cooling effect.

Wind Energy. Surface temperature changes in the vicinity of wind farms have been detected (Xia et al. 2019; Smith et al. 2013; Lee and Lundquist 2017; Takle et al. 2019) in the form of nighttime warming. Data from field campaigns suggest that a "suppression of cooling" can explain the observed warming (Takle et al. 2019). Regional and climate models have been used to describe the interactions between turbines and the atmosphere and find minor impacts (Vautard et al. 2014). More sophisticated models confirm the local warming effect of wind farms but report that the impact on the regional area is slight and occasional (Wang et al. 2019d). Wind turbines alter the transport and dissipation of momentum near the surface but do not directly impact the Earth's energy balance (Fischereit et al. 2021). However, the secondary modifications to the energy and water exchanges have added implications for the climate system (Jacobson and Archer 2012).

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), but emissions from organic matter decomposition decrease over time. The darker surface of the reservoir, compared to the lighter surrounding land may counterbalance part of the reduced GHG emissions by hydropower production (Wohlfahrt et al. 2021). However, these impacts vary significantly among facilities due to the surrounding land properties and the area inundated by the reservoir.

[END BOX 6.7 HERE

6.6 Key Characteristics of Net Zero Energy Systems

6.6.1 What is a Net Zero Energy System?

Limiting warming to well below 2°C requires that CO_2 emissions from the energy sector be reduced to near zero or even below zero (Chapter 3, 6.7). Policies, technologies, behaviours, investments, and other factors will determine the speed at which countries transition to net zero energy systems – those that emit very little or no emissions. An understanding of these future energy systems can help to chart a course toward them over the coming decades.

This section synthesizes current understanding of net zero energy systems. Discussions surrounding efforts to limit warming are frequently communicated in terms of the point in time at which net anthropogenic CO_2 emissions reach zero, accompanied by substantial reductions in non-CO_2 emissions

(IPCC 2018, Chapter 3). Net-zero GHG goals are also common, and they require net-negative CO_2 emissions to compensate for residual non-CO_2 emissions. Economy-wide CO_2 and GHG goals appear in many government and corporate decarbonization strategies, and they are used in a variety of ways. Most existing carbon-neutrality commitments from countries and subnational jurisdictions aim for economies with very low emissions rather than zero emissions. Offsets, carbon dioxide removal (CDR) methods, and/or land sink assumptions are used to achieve net zero goals (Kelly Levin et al. 2020).

Precisely describing a net zero energy system is complicated by the fact that different scenarios attribute different future CO_2 emissions to the energy system, even under scenarios where economy-wide CO_2 emissions reach net zero. It is also complicated by the dependence of energy system configurations on unknown future conditions like population and economic growth, and technological change. The energy system is not the only source or sink of CO_2 emissions. Terrestrial systems may store or emit carbon, and CDR options like BECCS or DACCS can be used to store CO_2, relieving pressure on the energy system (Chapter 3). The location of such CDR options is ambiguous, as it might be deployed within or outside of the energy sector (Figure 6.21), and many CDR options, such as DACCS, would be important energy consumers (Bistline and Blanford 2021a, 6.6.2). If CDR methods are deployed outside of the energy system (e.g., net negative agriculture, forestry, and land use CO_2 emissions), it is possible for the energy system to still emit CO_2 but have economy-wide emissions of zero or below. When global energy and industrial CO_2 emissions reach net zero, the space remaining for fossil energy emissions is determined by deployment of CDR options (Figure 6.21).

This section focuses on energy systems that produce very little or no CO_2 emissions, referred to in this chapter as net zero energy systems. While energy systems may not reach net zero concurrently with economy-wide CO_2 or GHG emissions, they are a useful benchmark for planning a path to net zero. Note that the focus here is on energy systems with net zero CO_2 emissions from fossil fuel combustion and industrial processes, but the lessons will be broadly applicable to net zero GHG energy systems as well. Net-zero GHG energy systems would incorporate the major efforts made to reduce non-CO_2 emissions (e.g., CH_4 from oil, gas and coal as discussed in Section 6.4) and would also need to incorporate more CDR to compensate for remaining non-CO_2 GHG emissions. Energy sector emissions in many countries may not reach net zero at the same time as global energy system emissions (Figure 6.25, Cross-Chapter Box 3 in Chapter 3).

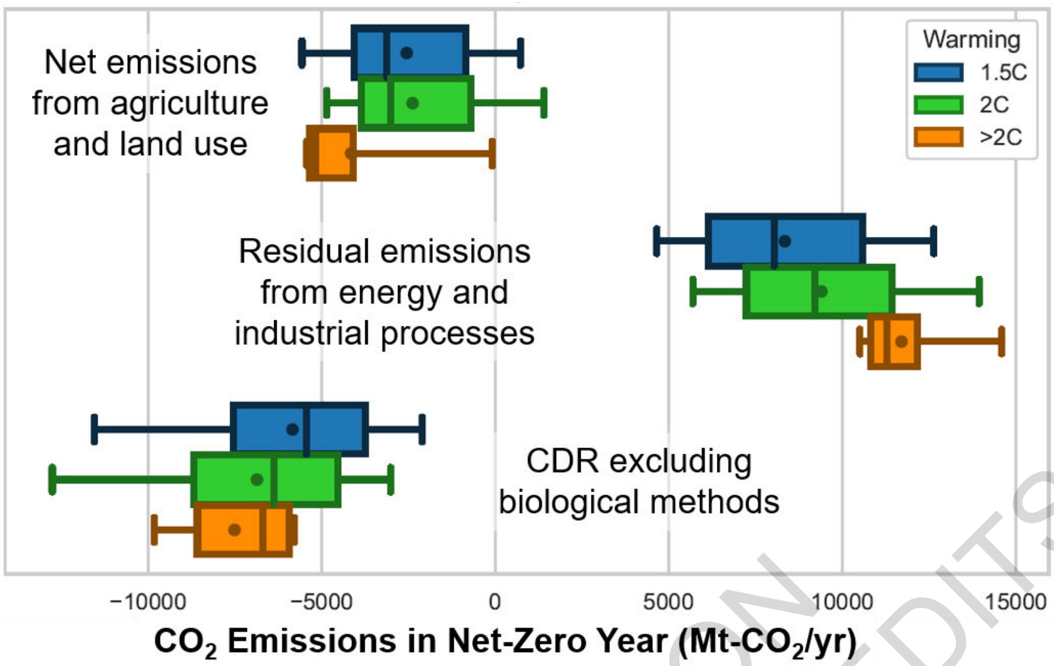


Figure 6.21 Residual emissions and CDR when global energy and industrial CO_2 emissions reach net zero. Residual emissions and CDR in net zero scenarios show global differences across warming levels (blue = <1.5˚C, green = <2.0˚C, orange = >2.0˚C). Points represent different models and scenarios from the AR6 database. In each case, the boxes show the 25th to 75th percentile ranges, and whiskers show the 5th and 95th percentiles. Lines and circles within the boxes denote the median and mean values, respectively.

6.6.2 Configurations of Net-zero Energy Systems

Net-zero energy systems entail trade-offs across economic, environmental, and social dimensions (Davis et al. 2018). Many socioeconomic, policy, and market uncertainties will also influence the configuration of net zero energy systems (van Vuuren et al. 2018; Krey et al. 2019; Bistline et al. 2019; Smith et al. 2015, Azevedo et al. 2021, Pye et al, 2021). There are 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 (Section 6.6.4 and Chapter 18 of WGII).

Explorations of net zero energy systems have been emerging in the detailed systems modelling literature (Azevedo et al. 2021; Bistline 2021b). Reports associated with net zero economy-wide targets for countries and subnational entities typically do not provide detailed roadmaps or modelling but discuss high-level guiding principles, though more detailed studies are emerging at national levels (Williams et al. 2021a; Duan et al. 2021; Capros et al. 2019; Wei et al. 2020). Most analysis has focused on identifying potential decarbonization technologies and pathways for different sectors, enumerating opportunities and barriers for each, their costs, highlighting robust insights, and characterizing key uncertainties (Hepburn et al. 2019; Davis et al. 2018).

The literature on the configuration of net zero energy systems is limited in a few respects. On the one hand, there is a robust integrated assessment literature that provides characterizations of these systems in broad strokes (AR6 database), offering internally consistent global scenarios to link global warming targets to regional/national goals. All integrated assessment scenarios that discuss net zero energy system CO_2 emissions provide high-level characterizations of net zero systems. Because these characterizations have less temporal, spatial, technological, regulatory, and societal detail, however, they may not consider the complexities that could ultimately influence regional, national, or local pathways. High-fidelity models and analyses are needed to assess the economic and environmental characteristics and the feasibility of many aspects of net zero or net negative emissions energy systems (*high confidence*) (Bistline and Blanford 2020; Blanford et al. 2018). For example, evaluating the competitiveness of electricity sector technologies requires temporal, spatial, and technological detail to accurately represent system investments and operations (Bistline 2021c; Victoria et al. 2021; Helistoe et al. 2019; Collins et al. 2017; Santen et al. 2017).

Configurations of net zero energy systems will vary by region but are likely to share several common characteristics (*high confidence*) (Figure 6.22). We focus on seven of those common characteristics in the remainder of this subsection.

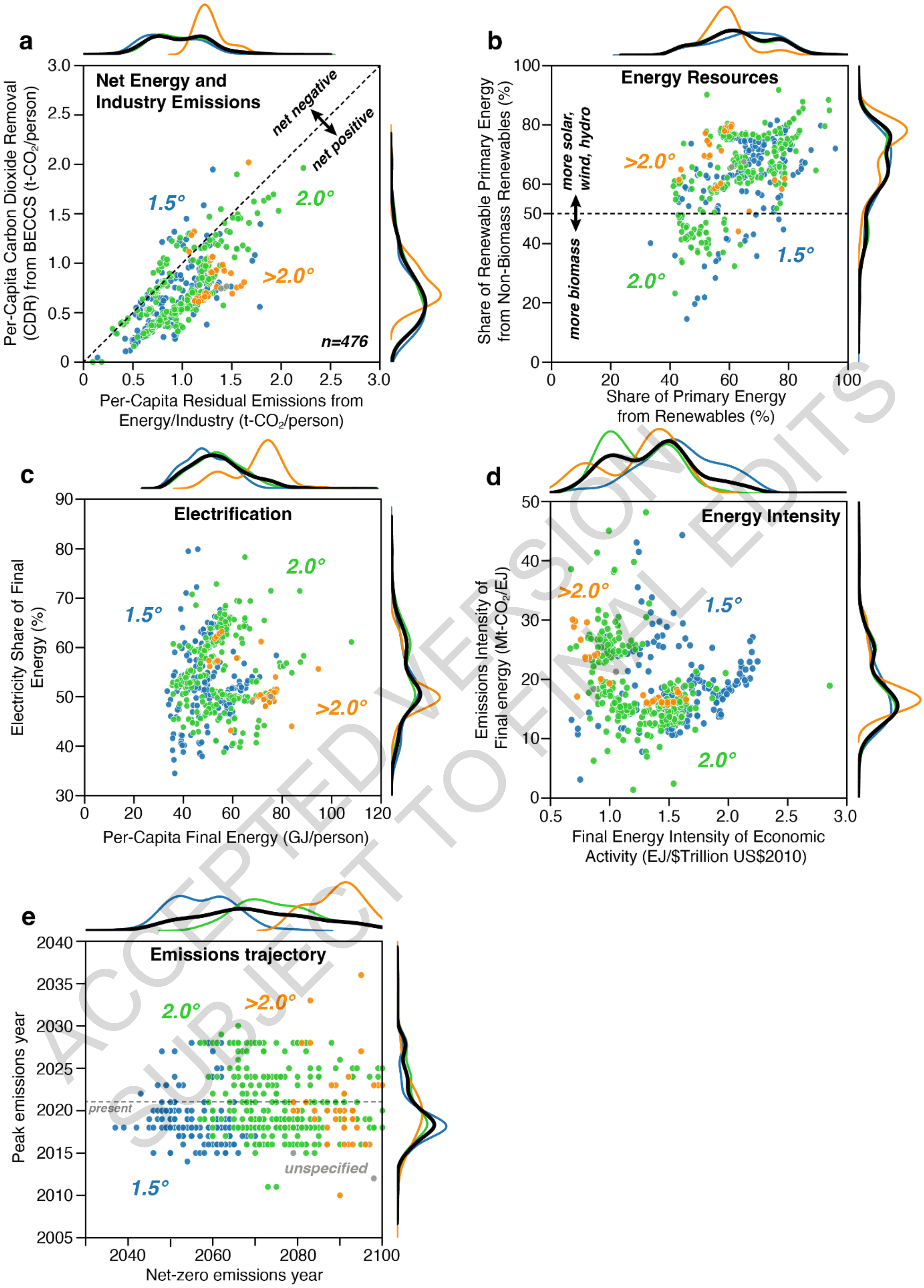


Figure 6.22 Characteristics of global net zero energy systems when global energy and industrial CO_2 emissions reach net zero. Scenarios reaching net zero emissions show differences in residual emissions

and carbon removal (a), energy resources (b), electrification (c), energy intensity (as measured here by energy GDP^{-1}) (d), and emissions trajectory (e), particularly with respect to warming levels (blue = <1.5˚C, green = <2.0˚C, orange = >2.0˚C, gray = unspecified). Points represent individual scenarios, with probability density distributions shown along each axis for each warming level (colours corresponding to warming levels) and for all scenarios (black). Points represent different models and scenarios from the AR6 database.

6.6.2.1 Limited and/or Targeted Use of Fossil Fuels

Net-zero energy systems will use far less fossil fuel than today (*high confidence*). The precise quantity of fossil fuels will largely depend upon the relative costs of such fuels, electrification, alternative fuels, and CDR (see Section 6.6.2.4) in the energy system (*high confidence*). All of these are affected by regional differences in resources (McGlade and Ekins 2015), existing energy infrastructure (Tong et al. 2019), demand for energy services, and climate and energy policies. Fossil fuel use may persist, for example, if and where the costs of such fuels and the compensating carbon management (e.g., CDR, CCS) are less than non-fossil energy. For most applications, however, it is likely that electrification (McCollum et al. 2014; Madeddu et al. 2020; Zhang and Fujimori 2020) or use of non-fossil alternative fuels (Zeman and Keith 2008; Graves et al. 2011; Hänggi et al. 2019; Ueckerdt et al. 2021) will prove to be the cheapest options. Most residual demand for fossil fuels is likely to predominantly be petroleum and natural gas given their high energy density (Davis et al. 2018), while demand for coal in net zero energy systems is likely to be very low (Luderer et al. 2018; Jakob et al. 2020, Section 6.7.4) (*high confidence*).

There is considerable flexibility regarding the overall quantity of liquid and gaseous fuels that will be required in net zero energy systems (*high confidence*) (Figure 6.22, Section 6.7.4). This will be determined by the relative value of such fuels as compared to systems which rely more or less heavily on zero-emissions electricity. In turn, the share of any fuels that are fossil or fossil-derived is uncertain and will depend on the feasibility of CCS and CDR technologies and long-term sequestration as compared to alternative, carbon-neutral fuels. Moreover, to the extent that physical, biological, and/or socio-political factors limit the availability of CDR (Smith et al. 2015; Field and Mach 2017), carbon management efforts may prioritize residual emissions related to land use and other non-energy sources.

6.6.2.2 Zero or Negative CO_2 Emissions from Electricity

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

There are many possible configurations and technologies for zero- or net-negative-emissions electricity systems (*high confidence*). These systems could entail a mix of variable renewables, dispatchable renewables (e.g., biomass, hydropower), other firm, dispatchable ("on-demand") low-carbon generation (e.g., nuclear, CCS-equipped capacity), energy storage, transmission, carbon removal options (e.g., BECCS, DACCS), and demand management (Bistline and Blanford 2021b; Bistline et al. 2018; Jenkins et al. 2018b; Luderer et al. 2017). The marginal cost of deploying electricity sector mitigation options increases as electricity emissions approach zero; in addition, the most cost-effective mix of system resources changes as emissions approach zero and, therefore, so do the implications of electricity sector mitigation for sustainability and other societal goals (Cole et al. 2021; Jayadev et al. 2020; Bistline et al. 2018; Mileva et al. 2016; Sepulveda et al. 2018). Key factors influencing the electricity mix include relative costs and system benefits, local resource bases, infrastructure availability, regional integration and trade, co-benefits, societal preferences and other policy priorities, all of which vary by country and region (Section 6.6.4). Many of these factors depend on when the net zero point is reached (Figure 6.22).

Based on their increasing economic competitiveness, VRE technologies, especially wind and solar power, will likely comprise large shares of many regional generation mixes (*high confidence*) (Figure 6.22). While wind and solar will likely be prominent electricity resources, this does not imply that 100% renewable energy systems will be pursued under all circumstances, since economic and operational challenges increase nonlinearly as shares approach 100% (Box 6.8) (Bistline and Blanford 2021a; Cole et al. 2021; Shaner et al. 2018; Frew et al. 2016; Imelda et al. 2018b). Real-world experience planning and operating regional electricity systems with high instantaneous and annual shares of renewable generation is accumulating, but debates continue about how much wind and solar should be included in different systems, and the cost-effectiveness of mechanisms for managing variability (Box 6.8). Either firm, dispatchable generation (including nuclear, CCS-equipped capacity, dispatchable renewables such as geothermal, and fossil units run with low capacity factors and CDR to balance emissions) or seasonal energy storage (alongside other balancing resources discussed in Box 6.8) will be needed to ensure reliability and resource adequacy with high percentages of wind and solar (Jenkins et al. 2018b; Dowling et al. 2020; Denholm et al. 2021) though each option involves uncertainty about costs, timing, and public acceptance (Albertus et al. 2020).

Electricity systems require a range of different functional roles – for example, providing energy, capacity, or ancillary services. As a result, a range of different types of generation, energy storage, and transmission resources may be deployed in these systems (Baik et al. 2021). There are many options for each of these roles, each with their strengths and weaknesses (Sections 6.4.3 and 6.4.4), and deployment of these options will be influenced by the evolution of technological costs, system benefits, and local resources (Veers et al. 2019; Mai et al. 2018; Bistline et al. 2018; Hirth 2015; Fell and Linn 2013).

System management is critical for zero- or negative-emissions electricity systems. Maintaining reliability will increasingly entail system planning and operations that account for characteristics of supply- and demand-side resources (Hu et al. 2018). Coordinated planning and operations will likely become more prevalent across portions of the electricity system (e.g., integrated generation, transmission, and distribution planning), across sectors, and across geographies (Bistline and Young 2019; Chan et al. 2018; Konstantelos et al. 2017; EPRI 2017, Section 6.4.3).

Energy storage will be increasingly important in net zero energy systems, especially in systems with shares of VRE (*high confidence*). Deployment of energy storage will vary based on the system benefits and values of different options (Arbabzadeh et al. 2019; Denholm and Mai 2019). Diurnal storage options like lithium-ion batteries have different value than storing and discharging electricity over longer periods through long-duration energy storage with less frequent cycling, which require different technologies, supporting policies, and business models (Sepulveda et al. 2021; Dowling et al. 2020; Gallo et al. 2016; Albertus et al. 2020; Blanco and Faaij 2017) (Section 6.4.4). The value of energy storage varies with the level of deployment and on the competitiveness of economic complements such as VRE options (Bistline and Young 2020; Mileva et al. 2016) and substitutes such as flexible demand (Brown et al. 2018; Merrick et al. 2018), transmission (Merrick et al. 2018; Brown et al. 2018; Schlachtberger et al. 2017; Bistline and Young 2019), trade (Bistline et al. 2020b), dispatchable generators (Hittinger and Lueken 2015; Gils et al. 2017; Arbabzadeh et al. 2019), DAC (Daggash et al. 2019), and efficiencies in system operations (Tuohy et al. 2015).

The approach to other sectors could impact electricity sector planning, and the role of some technologies (e.g., hydrogen, batteries, CCS) could depend on deployment in other sectors. CCS offers opportunities for CO_2 removal when fuelled with syngas or biomass containing carbon captured from the atmosphere (Hepburn et al. 2019); however, concerns about lifecycle environmental impacts, uncertain costs, and public acceptance are potential barriers to widespread deployment (Section 6.4.2). It is unclear whether CDR options like BECCS will be included in the electricity mix to offset continued emissions in other parts of the energy system or beyond (Mac Dowell et al. 2017; Luderer et al. 2018; Bauer et al. 2018a).

Some applications may also rely on PtX electricity conversion to create low-emissions synthetic fuels (Sections 6.6.2.6, 6.4.4, and 6.4.5), which could impact electricity system planning and operations. Additionally, if DAC technologies are used, electricity and heat requirements to operate DAC could impact electricity system investments and operations (Bistline and Blanford 2021a; Realmonte et al. 2019).

[START BOX 6.8 HERE]

Box 6.8 100% Renewables in Net Zero Energy Systems

The decreasing cost and increasing performance of renewable energy has generated interest in the feasibility of providing nearly all energy services with renewables. Renewable energy includes wind power, solar power, hydroelectric power, bioenergy, geothermal energy, tidal power, and ocean power. There are two primary frames around which 100% renewable energy systems are discussed: 100% renewable electricity systems and 100% renewable energy systems, considering not only electricity but all aspects of the energy system.

It is technically feasible to use very high renewable shares (e.g., above 75% of annual regional generation) to meet hourly electricity demand under a range of conditions, especially when VRE options, notably wind and solar, are complemented by other resources (*high confidence*). There are currently many grids with high renewable shares and large anticipated roles for VRE sources, in particular wind and solar (see Section 6.4), in future low-carbon electricity systems. An increasingly large set of studies examines the feasibility of high renewable penetration and economic drivers under different policy, technology, and market scenarios (Denholm et al. 2021; Blanford et al. 2021; Bistline et al. 2019; Hansen et al. 2019; Jenkins et al. 2018b; Cochran et al. 2014; Dowling et al. 2020; Deason 2018). High wind and solar penetration involves technical and economic challenges due to their unique characteristics such as spatial and temporal variability, short- and long-term uncertainty, and non-synchronous generation (Cole et al. 2017). These challenges become increasingly important as renewable shares approach 100% (Sections 6.6.2.2 and 6.4.3).

There are many balancing options in systems with very high renewables (Denholm et al. 2021; Bistline 2021a; Mai et al. 2018; Milligan et al. 2015; Jenkins et al. 2018b).

- **Energy storage:** Energy storage technologies like batteries, pumped hydro, and hydrogen can provide a range of system services (Balducci et al. 2018; Bistline et al. 2020a; Section 6.4.4). Lithium-ion batteries have received attention as costs fall and installations increase, but very high renewable shares typically entail either dispatchable generation or long-duration storage in addition to short-duration options (Schill 2020; Arbabzadeh et al. 2019; Jenkins et al. 2018b). 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 (Castillo and Gayme 2014; EPRI 2019a).
- **Transmission and trade:** To balance differences in resource availability, high renewable systems will very likely entail investments in transmission capacity (Zappa et al. 2019; Pleßmann and Blechinger 2017; Macdonald et al. 2016; Mai and Et al 2014; Section 6.4.5) and changes in trade (Abrell and Rausch 2016; Bistline et al. 2019). These increases will likely be accompanied by expanded balancing regions to take advantage of geographical smoothing.
- **Dispatchable ("on-demand") generation:** Dispatchable generation could include flexible fossil units or low-carbon fuels such as hydrogen with lower minimum load levels (Bistline 2019; Denholm et al. 2018), renewables like hydropower, geothermal, or biomass (Hansen et al. 2019; Hirth 2016), or flexible nuclear (Jenkins et al. 2018a). The composition depends on costs and other policy goals, though in all cases, capacity factors are low for these resources (Mills et al. 2020).
- **Demand management:** Many low-emitting and high-renewables systems also utilize increased load flexibility in the forms of energy efficiency, demand response, and demand flexibility, utilizing

newly electrified end uses such as electric vehicles to shape demand profiles to better match supply (Bistline 2021a; Imelda et al. 2018a; Hale 2017; Brown et al. 2018; Ameli et al. 2017).

- **Sector coupling:** Sector coupling includes increased end-use electrification and PtX electricity conversion pathways, which may entail using electricity to create synthetic fuels such as hydrogen (Ueckerdt et al. 2021; Davis et al. 2018) (see Sections 6.4.3, 6.4., 6.4.5, 6.6.4.3, and 6.6.4.6).

Deployment of integration options depends on their relative costs and value, regulations, and electricity market design. There is considerable uncertainty about future technology costs, performance, availability, scalability, and public acceptance (Kondziella and Bruckner 2016; Bistline et al. 2019). Deploying balanced resources likely requires operational, market design, and other institutional changes, as well as technological changes in some cases (Denholm et al. 2021; Cochran et al. 2014). Mixes will differ based on resources, system size, flexibility, and whether grids are isolated or interconnected.

Although there are no technical upper bounds on renewable electricity penetration, the economic value of additional wind and solar capacity typically decreases as their penetration rises, creating economic challenges at higher deployment levels (Denholm et al. 2021; Millstein et al. 2021; Cole et al. 2021; Gowrisankaran et al. 2016; Hirth 2013). The integration options above, as well as changes to market design, can mitigate these challenges but likely will not solve them, especially since these options can exhibit declining value themselves (Denholm and Mai 2019; Bistline 2017; De Sisternes et al. 2016) and may be complements or substitutes to each other.

Energy systems that are 100% renewable (including all parts of the energy sector, and not only electricity generation) raise a range of technological, regulatory, market, and operational challenges that make their competitiveness uncertain (*high confidence*). These systems require decarbonizing all electricity, using this zero-carbon electricity broadly, and then utilizing zero-carbon energy carriers for all end uses not served by electricity, for example, air travel, long-distance transport, and high-temperature process heat. Broader questions emerge regarding the attractiveness of supplying all energy, and not just electricity, with renewables (Figure 6.22). Integrated assessment and energy systems research suggest large roles for renewables, but energy and electricity shares are far from 100%, even with stringent emissions reductions targets and optimistic assumptions about future cost reductions (Huntington et al. 2020; Jenkins et al. 2018b; Bauer et al. 2018; Bistline et al. 2018, Section 6.7.1). Scenarios with 100% renewable energy systems are an emerging subset in the decarbonization literature, especially at regional levels (Denholm et al. 2021; Hansen et al. 2019). Many 100% renewables studies focus more heavily on electrification for decarbonizing end uses, and include less biofuels and hydrogen than the broader literature on deep decarbonization (Bauer et al. 2018a). These studies typically assume a constrained set of available technologies to demonstrate the technical feasibility of very high renewable systems and do not optimize to find least-cost, technology-neutral decarbonization pathways, and many 100% renewables studies focus on the electricity sector or a limited number of sectors (Hansen et al. 2019; Jenkins et al. 2018a). In addition to renewables, studies broadly agree that including additional low-carbon options – including not only low-carbon electricity but also targeted use of fossil fuels with and without CCS (Section 6.6.2.1) and alternative fuels for sectors that are difficult to electrify (Section 6.6.2.4) – can lower the cost of decarbonization even with very high shares of renewables (Figure 6.22). However, there is disagreement about the magnitude of cost savings from larger portfolios, which depend on context- and scenario-specific assumptions about technologies, markets, and policies.

[END BOX 6.8 HERE]

6.6.2.3 Widespread Electrification of End Uses

Net-zero energy systems will rely more heavily on increased use of electricity (electrification) in end uses (*high confidence*). The literature on net zero energy systems almost universally calls for increased electrification (Williams et al. 2012; Sugiyama 2012; Williams et al. 2014; Rogelj et al. 2015a; Sachs et al. 2016; Kriegler et al. 2014a; Sven et al. 2018; Luderer et al. 2018; Schreyer et al. 2020). At least 30% of the global final energy needs are expected to be served by electricity, with some estimates suggesting upwards of 80% of total energy use being electrified (Figure 6.22, panel c). Increased electrification is especially valuable in net zero energy systems in tandem with decarbonized electricity generation or net-negative emissions electricity generation (Section 6.5.4.2). Flexible electric loads (electric vehicles, smart appliances) can in turn facilitate incorporation of VRE electricity options, increase system flexibility, and reduce needs for grid storage (Section 6.4.3) (Mathiesen et al. 2015); Lund et al., 2018).

Several end-uses such as passenger transportation (light-duty electric vehicles, two and three wheelers, buses, rail) as well as building energy uses (lighting, cooling) are likely to be electrified in net zero energy systems (*high confidence*). Variations in projections of electrification largely result from differences in expectations about the ability and cost-competitiveness of electricity to serve other end uses such as non-rail freight transport, aviation, and heavy industry (McCollum et al. 2014; Breyer et al. 2019; Bataille et al. 2016; EPRI 2018) (Section 6.5.4.4), especially relative to biofuels and hydrogen ('low carbon fuels') (Sachs et al. 2016; Rockström et al. 2017; McCollum et al. 2014), the prospects for which are still quite uncertain (Section 6.4). The emergence of CDR technologies and the extent to which they allow for residual emissions as an alternative to electrification will also affect the overall share of energy served by electricity (Section 6.6.2.7).

Regions endowed with cheap and plentiful low-carbon electricity resources (wind, solar, hydropower) are likely to emphasize electrification, while those with substantial bioenergy resources or availability of other liquid fuels might put less emphasis on electrification, particularly in hard-to-electrify end-uses (*medium confidence*). For example, among a group of Latin American countries, relative assumptions about liquid fuels and electricity result in an electrification range of 28–82% for achieving a net zero energy system (Bataille et al. 2020). Similarly, the level of penetration of biofuels that can substitute for electrification will depend on regional circumstances such as land-use constraints, competition with food, and sustainability of biomass production (Section 6.6.2.4).

Electrification of most buildings services, with the possible exception of space heating in extreme climates, is expected in net zero energy systems (*high confidence*) (Chapter 9). Space cooling and water heating are expected to be largely electrified. Building electrification is expected to rely substantially on heat pumps, which will help lower emissions both through reduced thermal requirements and higher efficiencies (Mathiesen et al. 2015; Rissman et al.; Sven et al. 2018). The level of electrification for heating will depend on the tradeoffs between building or household level heat pumps versus more centralized district heating network options (Mathiesen et al. 2015; Brown et al. 2018), as well as the cost and performance of heat pumps in more extreme climates and grid infrastructure (EPRI 2018; Waite and Modi 2020).

A significant share of transportation, especially road transportation, is expected to be electrified in net zero energy systems (*high confidence*). In road transportation, two-three wheelers, light-duty vehicles (LDVs), and buses, are especially amenable to electrification, with more than half of passenger LDVs expected to be electrified globally in net zero energy systems (*medium confidence*) ((Bataille et al. 2020; Sven et al. 2018; Khalili et al. 2019; Fulton et al. 2015). Long-haul trucks, large ships, and aircraft are expected to be harder to electrify absent technological breakthroughs (Mathiesen et al. 2015; Fulton et al. 2015), although continued improvements in battery technology may enable electrification of long-haul trucks (Nykvist and Olsson 2021; Chapter 10). Due to the relative ease of rail electrification, near complete electrification of rail and a shift of air and truck freight to rail is expected in net zero energy systems (Sven et al. 2018; Khalili et al. 2019; Rockström et al. 2017; Fulton et al. 2015). The degree of modal shifts and electrification will depend on local factors such as infrastructure availability and location accessibility. Due to the challenges associated with electrification of some transport modes, net zero energy systems may include some residual emissions associated with the freight sector that are offset through CDR technologies (Muratori et al. 2017b), or reliance on low and zero-carbon fuels instead of electrification.

A non-trivial number of industry applications could be electrified as a part of a net zero energy system, but direct electrification of heavy industry applications such as cement, primary steel manufacturing, and chemical feedstocks is expected to be challenging (*medium confidence*) (Davis et al. 2018; Madeddu et al. 2020; Philibert 2019; van Sluisveld et al. 2021). Process and boiler heating in industrial facilities are anticipated to be electrified in net zero energy systems. Emissions intensity reductions for cement and concrete production can be achieved through the use of electrified cement kilns, while emissions associated with steel production can be reduced through the use of an electric arc furnace (EAF) powered by decarbonized electricity (Rissman et al.). Electricity can also be used to replace thermal heat such as resistive heating, electric arc furnaces, and laser sintering (Rissman et al.; Madeddu et al. 2020). One study found that as much as 60% of the energy end-use in European industry could be met with direct electrification using existing and emerging technologies (Madeddu et al. 2020). Industry electrification for different regions will depend on the economics and availability of alternative emissions mitigation strategies such as carbon neutral fuels and CCS (Davis et al. 2018; Madeddu et al. 2020).

6.6.2.4 Alternative Fuels in Sectors not Amenable to Electrification

Net-zero energy systems will need to rely on alternative fuels – notably hydrogen or biofuels – in several sectors that are not amenable to electricity and otherwise hard to decarbonize (*medium confidence*). Useful carbon-based fuels (e.g., methane, petroleum, methanol), hydrogen, ammonia, or alcohols can be produced with net zero CO_2 emissions and without fossil fuel inputs (Sections 6.4.4 and 6.4.5). 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). The resulting energy-dense fuels can serve applications that are difficult to electrify, 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 through, for example, CCS or CDR (Ueckerdt et al. 2021)

CO_2 emissions from some energy services are expected to be particularly difficult to cost-effectively avoid, among them aviation; long-distance freight by ships; process emissions from cement and steel production; high-temperature heat (e.g., >1000°C); and electricity reliability in systems with high penetration of variable renewable energy sources (NAS; Davis et al. 2018; Luderer et al. 2018; Chiaramonti 2019; Sepulveda et al. 2018; Bataille 2020; Rissman et al.; Thiel and Stark 2021; Madeddu et al. 2020). The literature focused on these services and sectors is growing, but remains limited, and provides minimal guidance on the most promising or attractive technological options and systems for avoiding these sectors' emissions. Technological solutions do exist, but those mentioned in the literature are prohibitively expensive, exist only at an early stage, and/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-electrify sectors, but face substantial challenges related to their life-cycle carbon emissions, cost, and further scalability (Tilman et al. 2009; Staples et al. 2018), (Section 6.4.2). The extent to which biomass will supply liquid fuels or high temperature heat for industry in a future net zero energy system will thus depend on advances in conversion technology that enable use of feedstocks such as woody crops, agricultural residues, algae, and wastes, as well as competing demands for bioenergy and land, the feasibility of other sources of carbon-neutral fuels, and integration of bioenergy production with other objectives, including CDR, economic development, food security, ecological conservation, and air quality (Lynd 2017; Laurens 2017; Williams and Laurens

2010; Strefler et al. 2018; Bauer et al. 2018a; Fargione 2010; Creutzig et al. 2015; Bauer et al. 2018b; Muratori et al. 2020b; Chatziaras et al. 2016; Fennell et al. 2021) (Section 6.4.2.6).

Costs are the main barrier to synthesis of net zero emissions fuels (*high confidence*), particularly costs of hydrogen (a constituent of hydrocarbons, ammonia, and alcohols) (Section 6.4.5). 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 USD kg^{-1} (Sherwin 2021). Non-fossil hydrogen can be obtained by electrolysis of water, at current costs of 5-7 USD kg^{-1} H_2^{-1} (assuming relatively low electricity costs and high utilization rates) (Graves et al. 2011; Newborough and Cooley 2020; Peterson et al. 2020; DOE 2020a). At these costs for electrolytic hydrogen, synthesized net zero emissions fuels would cost at least 1.6 USD per liter of diesel equivalent (or 6 USD $gallon^{-1}$ and 46 USD GJ^{-1}, assuming non-fossil carbon feedstock costs of 100 USD per ton of CO_2 and low process costs of 0.05 USD $liter^{-1}$ or 1.5 USD GJ^{-1}). Similar calculations suggest that synthetic hydrocarbon fuels could currently avoid CO_2 emissions at a cost of 936-1404 USD ton^{-1} (Ueckerdt et al. 2021). However, economies of scale are expected to bring these costs down substantially in the future (Ueckerdt et al. 2021; IRENA 2020c), and R&D efforts are targeting 60-80% reductions in costs (to less than 2 USD kg^{-1} $(H2)^{-1}$) possibly by use of less mature but promising technologies such as high-temperature electrolysis and thermochemical water splitting (Schmidt et al. 2017; Pes et al. 2017; DOE 2018; Saba et al. 2018; Kuckshinrichs et al. 2017; DOE 2020b). Technologies capable of producing hydrogen directly from water and sunlight (photoelectrochemical cells or photocatalysts) are also under development, but still at an early stage (DOE 2020a; 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 net zero emissions fuel production at scale (DOE 2020a; Newborough and Cooley 2020; McKone et al. 2014).

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

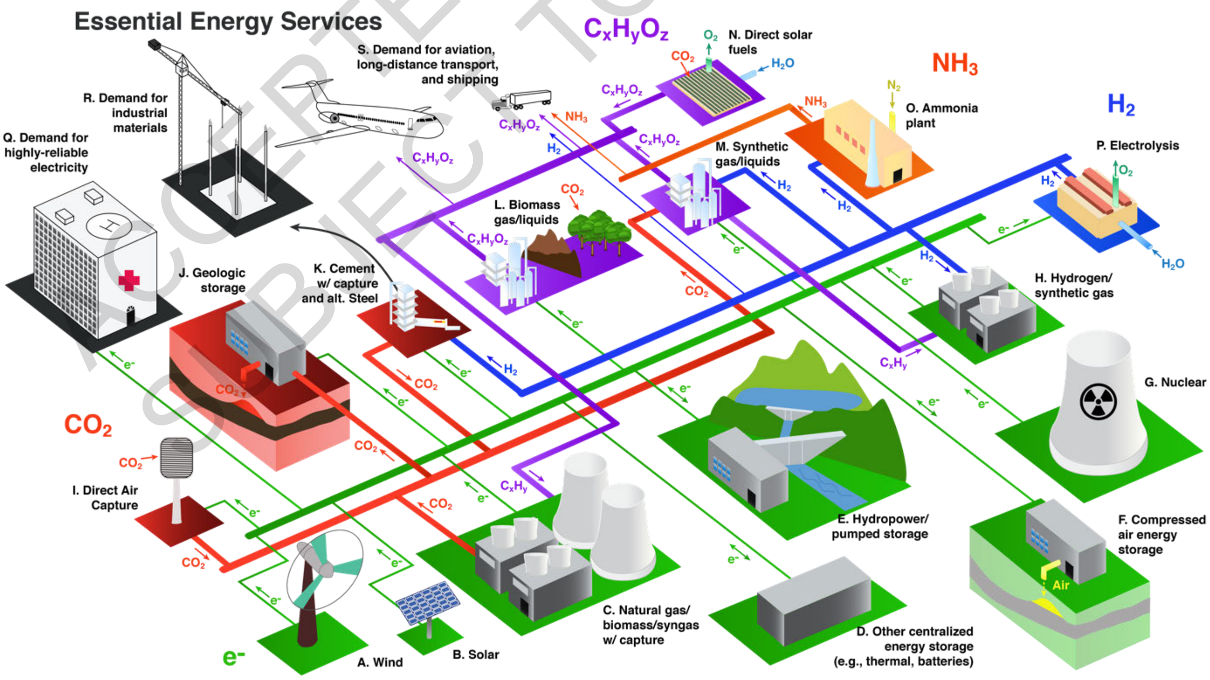


Figure 6.23 Schematic of net zero emissions energy system, including methods to address difficult-to-electrify sectors. (Source: Davis et al. 2018)

[START BOX 6.9 HERE]

Box 6.9 The Hydrogen Economy

The phrase "hydrogen economy" is often used to describe future energy systems in which hydrogen plays a prominent role. These future energy systems would not use hydrogen for all end uses; they would use hydrogen to complement other energy carriers, mainly electricity, where hydrogen might have advantages. Hydrogen could provide long-term electricity storage to support high-penetration of intermittent renewables and could enable trading and storage of electricity between different regions to overcome seasonal or production capability differences (Dowling et al. 2020; Sepulveda et al. 2021). It could also be used in lieu of natural gas for peaking generation, provide process heat for industrial needs, or be used in the metal sector via direct reduction of iron ore (Chapter 11). Clean hydrogen could be used as a feedstock in the production of various chemicals and synthetic hydrocarbons. Finally, hydrogen-based fuel cells could power vehicles. Recent advances in battery storage make electric vehicles the most attractive alternative for light-duty transport. However, fuel cell technology could complement electric vehicles in supporting the decarbonisation of heavy-duty transport segments (e.g., trucks, buses, ships, and trains) (Chapter 10).

Hydrogen production costs have historically been prohibitive, but recent technological developments are bringing costs down. These developments include improvements in hydrogen production technologies in terms of efficiency and capital costs (e.g., SMR) (Alrashed and Zahid 2021; Boretti and Banik 2021) and the emergence of alternative production technologies such as electrolysers (Dawood et al. 2020). These technological changes, along with decreasing costs of renewable power, are increasing the viability of hydrogen. Other improvements in hydrogen-based technologies are also emerging quickly. Gas turbines now run on blended fuels containing 5-95% hydrogen by volume (GE 2020) and could operate entirely on hydrogen by 2030 (Pflug et al. 2019). Fuel cell costs have decreased by 80-95% since the early 2000s, while power density and durability have improved (Kurtz et al. 2019; IEA 2019e; Jouin et al. 2016).

For hydrogen to support decarbonisation, it will need to be produced from zero-carbon or extremely low-carbon energy sources. One such production category is "green hydrogen." While there is no unified definition for green hydrogen, it can be produced by the electrolysis of water using electricity generated without carbon emissions (such as renewables). Hydrogen can also be produced through biomass gasification with CCS (BECCS), leading to negative carbon emissions (del Pozo et al. 2021). Additionally, "blue hydrogen" can be produced from natural gas through the process of auto-thermal reforming (ATR) or steam methane reforming (SMR), combined with CCS technology that would absorb most of the resulting CO_2 (80-90%).

However, the potential role of hydrogen in future energy systems depends on more than just production methods and costs. For some applications, the competitiveness of hydrogen also depends on the availability of the infrastructure needed to transport and deliver it at relevant scales (Lee et al. 2021). Transporting hydrogen through existing gas pipelines is generally not feasible without changes to the infrastructure itself (Muratori et al. 2018; Gumber and Gurumoorthy 2018). Existing physical barriers, such as steel embrittlement and degradation of seals, reinforcements in compressor stations, and valves, require retrofitting during the conversion to H_2 distribution or new H_2 dedicated pipelines to be constructed (Dohi et al. 2016). The capacity to leverage and convert existing gas infrastructure to transport hydrogen will vary regionally, but in many cases could be the most economically viable pathway (Brändle et al. 2021; Cerniauskas et al. 2020; Brooks 2021; Wettengel 2021). Hydrogen could also be transported as liquid gas or as liquid organic hydrogen carriers such as ammonia, for which industry knowledge exists (Hong et al. 2021; Wulf et al. 2018; Demir et al. 2018). Additionally, improvements in fuel cell technologies are needed to make hydrogen-based transport economically viable. There are also safety concerns associated with the flammability (Nilsson et al. 2017) and storage (Andersson and Grönkvist 2019; Caglayan et al. 2019) of hydrogen which will need to be considered.

[END BOX 6.9 HERE]

6.6.2.5 Using Less Energy and Using It More Efficiently

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

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

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

Measurement issues notwithstanding, virtually all studies that address net zero energy systems assume improved energy intensity in the future (*high confidence*). The overall efficiency outcomes and the access to such improvements across different nations, however, is not clear. Energy consumption will increase over time despite energy efficiency improvements due to population growth and development (DeAngelo et al. 2021).

A study (DeAngelo et al. 2021) reviewed 153 IAM scenarios that attain net zero energy sector CO2 emissions and found that, under a scenario with net zero emissions: global final energy per capita lies between 21–109 GJ per person (median: 57), in comparison to 2018 global final energy use of 55 GJ per person; many countries use far more energy per capita than today as their incomes increase; global final energy use per unit of economic output ranges from 0.7–2.2 EJ per trillion USD (median: 1.5), in comparison to 5 EJ per trillion USD in 2018; and the median final energy consumption is 529 EJ. By comparison, final energy consumption would be 550 EJ if current energy consumption per capita continued under a future population of 10 billion people. Across all scenarios, total final energy consumption is higher today than in the year in which net zero emissions are attained, and regionally, only the OECD+EU and Eurasia have lower median total final energy than in 2010.

Net-zero energy systems will be characterized by greater efficiency and more efficient use of energy across all sectors (*high confidence*). Road transportation efficiency improvements will require a shift from liquid fuels (Chapters 5 and 10). Emissions reductions will come from a transition to electricity, hydrogen, or synthetic fuels produced with low carbon energy sources or processes. Vehicle automation, ride-hailing services, online shopping with door delivery services, and new solutions like last mile delivery with drones may result in increased service share. Lighter vehicles, a shift to public transit, and incorporation of 2- and 3-wheelers will be features of a net zero energy system (Chapter 10). Teleworking and automation of work may provide reductions in driving needs. Other sectors, such as air travel and marine transportation may rely on alternative fuels such as biofuels, synthetic fuels, ammonia, produced with zero carbon energy source (Section 6.6.2.4).

Under net zero energy systems, buildings would by characterized by improved construction materials, an increase in multi-family dwellings, early retirement of inefficient buildings, smaller floor areas, and smart controls to optimize energy use in the building, namely for heating, cooling, LED lighting, and water heating (Chapter 9). End-uses would utilize electricity, or potentially hydrogen, produced from zero carbon sources. The use of electricity for heating and cooking may often be a less efficient process at converting primary energy to energy services than using natural gas, but using natural gas would require CDR in order to be considered net zero emissions. Changes in behaviour may modestly lower demand. Most economies would have buildings with more efficient technologies powered by zero carbon electricity, and developing economics would shift from biomass to electricity, raising their energy consumption as population and wealth increase under net zero energy systems.

Industry has seen major efficiency improvements in the past, but many processes are now close to their thermodynamic limits. Electrification and breakthrough processes (such as producing steel with electricity and H_2), using recycled materials, using heat more efficiently by improving thermal insulation, and using waste heat for heat pumps, as well using advanced sensors, monitoring, and visualization and communication technologies may provide further efficiency improvements. (Chapter 11)

6.6.2.6 Greater Reliance on Integrated Energy System Approaches

Energy systems integration refers to connected planning and operations across energy carriers, including electricity, fuels, and thermal resources. Coordinated planning could be important in lowering system costs, increasing reliability, minimizing environmental impacts, and ensuring that costs of R&D and infrastructure account for not just current needs but also for those of future energy systems (Section 6.4.3). Integration includes not only the physical energy systems themselves but also simultaneous societal objectives (e.g., sustainable development goals), innovation processes (e.g., coordinating R&D to increase the likelihood of beneficial technological spillovers), and other institutional and infrastructural transformations (Sachs et al. 2019). Given system variability and differences in regional resources, there are economic and technical advantages to greater coordination of investments and policies across jurisdictions, sectors, and levels of government (Schmalensee and Stavins 2017). Coordinated planning and operations can improve system economics by sharing resources, increasing the utilization of capital-intensive assets, enhancing the geographical diversity of resource bases, and smoothing demand. But integration could require regulatory and market frameworks to facilitate and appropriate price signals to align incentives and to coordinate investments and operations.

Carbon-neutral energy systems are likely to be more interconnected than those of today (*high confidence*). The many possible feedstocks, energy carriers, and interconversion processes imply a greater need for the integration of production, transport, storage, and consumption of different fuels (Davis et al. 2018). For instance, electrification is expected to play an important role in decarbonizing light-duty vehicles (Chapter 10, Section 6.4.3), yet the electricity and transport sectors have few direct interactions today. Systems integration and sectoral coupling are increasingly relevant to ensure that net zero energy systems are reliable, resilient, and affordable (EPRI 2017; O'Malley et al. 2020; Buttler and Spliethoff 2018; Martin et al. 2017). Deep decarbonization offers new opportunities and challenges for integrating different sectors as well as supply- and demand-side options. For instance, increasing electrification will change daily and seasonal load shapes, and end-use flexibilities and constraints could impact the desirability of different supply-side technologies (EPRI 2019b; Brown et al. 2018). The feasibility of net zero energy system configurations could depend on demonstrating cross-sector benefits like balancing VRE sources in the electricity sector, and on offering the flexibility to produce multiple products. For instance, low-emissions synthetic fuels could help to bridge stationary and mobile applications, since fuel markets have more flexibility than instantaneously balanced electricity markets due to the comparative ease and cost of large-scale, long-term storage of chemical fuels (Davis et al. 2018).

There are few detailed archetypes of integrated energy systems that provide services with zero- or net-negative CO_2 emissions (such as (Jacobson et al. 2019)), so there is considerable uncertainty about integration and interactions across parts of the system. Although alternate configurations, tradeoffs, and pathways are still being identified, common elements include fuels and processes like zero- or negative-CO_2 electricity generation and transmission, hydrogen production and transport, synthetic hydrocarbon production and transport, ammonia production and transport, and carbon management, where linkages across pathways could include the use of electricity to produce hydrogen via electrolysis (Davis et al. 2018; Jenkins et al. 2018b; van Vuuren et al. 2018; Shih et al. 2018; Moore 2017; Smith et al. 2016). Linked analytical frameworks are increasing being used to understand the potential role for system coupling with greater temporal resolution, spatial resolution, and heterogeneity of consumer and firm decisions (Pye et al. 2021; Gerboni et al. 2017; Santen et al. 2017; Collins et al. 2017; Bistline and de la Chesnaye 2017; Bohringer and Rutherford 2008).

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

6.6.2.7 Carbon Dioxide Removal

While CDR is likely necessary for net zero energy systems, the scale and mix of strategies is unclear – nonetheless some combination of BECCS and DACCS are likely to be part of net zero energy systems (*high confidence*). Studies indicate that energy-sector CDR may potentially remove 5–12 $GtCO_2$ annually globally in net zero energy systems (Fuss et al. 2018) (Figure 6.22; Section 6.7; Chapter 12). CDR is not intended as a replacement for emissions reduction, but rather as a complementary effort to offset residual emissions from sectors that are not decarbonized and from other low-carbon technologies such as fossil CCS (McLaren et al. 2019; Gaffney et al. 2020; Iyer et al. 2021).

CDR covers a broad set of methods and implementation options (Chapters 7 and 12). The two CDR methods most relevant to the energy sector are BECCS, which is used to produce energy carriers, and DACCS which is an energy user (Smith et al. 2016; Singh and Colosi 2021). BECCS has value as an electricity generation technology, providing firm, dispatchable power to support electricity grids with large amounts of VRE sources, and reducing the reliance on other means to manage these grids, including electricity storage (Bistline and Blanford 2021a; Mac Dowell et al. 2017). BECCS may also be used to produce liquid fuels or gaseous fuels, including hydrogen (Section 6.4.2.6) (Muratori et al. 2020b). For instance, CO_2 from bio-refineries could be captured at <45 USD tCO_2^{-1} (Sanchez et al. 2018). Similarly, while CO_2 capture is expensive, its integration with hydrogen via biomass gasification can be achieved at an incremental capital cost of 3-35% ((Muratori et al. 2020b); Section 6.4). As with all uses of bioenergy, linkages to broad sustainability concerns may limit the viable development, as will the presence of high-quality geologic sinks in close proximity (Melara et al. 2020).

DACCS offers a modular approach to CDR (Creutzig et al. 2019), but it could be a significant consumer of energy. DAC could also interact with other elements of the energy systems as the captured CO_2 could be reused to produce low-carbon methanol and other fuels (Realmonte et al. 2019; Hoppe et al. 2018; Zhang and Fujimori 2020). DACCS might also offer an alternative for use of excess electricity produced by variable renewables (Wohland et al. 2018), though there are uncertainties about the economic performance of this integrated approach.

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

The transition to net zero energy systems is not just technological; it requires shifts in institutions, organizations, and society more generally. As such, it involves institutional changes alongside changes in supply, technology, or markets (Andrews-Speed 2016, Pai et al. 2021). Institutional relationships between governments and energy sector actors (e.g., consumers, electricity companies) affect the nature of net zero systems, as these entities may collaborate on or dispute net zero goals and measures to achieve them. For example, following the Fukushima disaster, Japan placed emphasis on government-utility-public cooperation on use of nuclear power as a means of reducing carbon emissions (Sklarew 2018). Institutions are instrumental in shaping net zero energy systems in multiple ways, complemented by and interacting with the behaviours of actors and policy regimes in these systems (Figure 6.24).

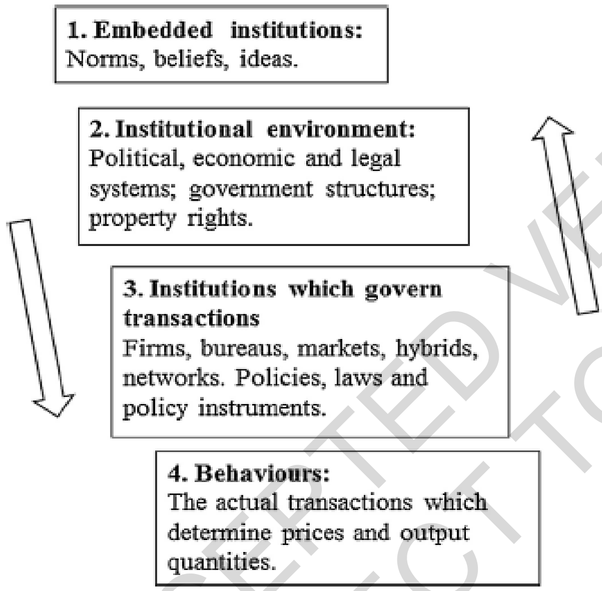


Figure 6.24 A four-level framework for institutional change. The diagram depicts three levels of institutions (1-3) which collectively govern actor behaviours (4). Source: Andrews-Speed 2016

One level of institutional interactions reflects embedded institutions, norms, beliefs, and ideas that would need to change to support net zero energy systems. This applies, for example, to the objectives of modern economies and the potentially contradictory dynamics embedded in the concept of "green growth" (Stegemann and Ossewaarde 2018; Stoknes and Rockström 2018). The institutional environment – the political and legal systems that govern exchanges and protect property rights – would also need to be different in net zero energy systems. In this setting, changing regulations or subsidies that continue to favour carbon-intensive systems over the technologies of a net zero energy system might prove difficult (Sovacool 2017). More generally, net zero energy systems will need new regulatory frameworks to undertake new challenges, from managing a more interconnected grid to adequately governing underground storage of CO_2. Institutions may also govern specific transactions, such as firms or networks that supply energy fuels or services. Current actors are typically resistant to disruptions, even if such disruptions may broadly benefit society (Kungl 2015, Mori 2018, Schmid et al. 2017).

For example, one energy system characterized by differentiated institutional interactions is the United States, where delivery of liquid fuels is lightly regulated, while electricity delivery is closely regulated (Dworkin et al. 2013). Reforming this two-pronged system for decarbonization would require four types of institutional change: (1) changes to the control systems that coordinate generation and transmission through a pyramidal architecture for the operational control, dispatch, and delivery of electricity with a primary emphasis on reliability; (2) changes to the financing of central-station power plants through long-term bonds, as valued by Wall Street ratings analysts; (3) 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) changes to regulations to restructure and limit excessive returns and easy entry of new retail competitors, all recognizing local and national concerns through state and federal regulatory agencies. The example shows how decision-making and the infrastructures involved are layered, and can create "nested hierarchies" where institutions fulfill multiple roles for energy governance or regulation simultaneously (Stern et al. 2016b). Internationally and across different parts of the energy system, institutional challenges such as these could become even more stark and complex (Van de Graaf 2013).

6.6.4 Regional Circumstances and Net-zero Energy Systems

Countries have flexibility to pursue options that make the most sense for their national circumstances (Figure 6.25). They may emphasize supply transformation over demand reduction; deploy different resources; engage at different levels in international energy trade; support different energy industries; focus on different energy carriers (e.g., electricity, hydrogen); or focus more on distributed or integrated systems, among others. Many factors may influence the long-term net zero energy systems that are appropriate for any country's national circumstances, including the following.

Future Technology. Technological transitions have often been driven by the relative merits of different technology options. Recent trends in the use of PV cells, wind power, and in batteries, for example, have been spurred by their increasing economic competitiveness (Section 6.3). Yet future technology cannot be fully predicted, so it provides only a partial guide today for charting a path toward future systems.

Indigenous Energy Resources. Countries may emphasize approaches that take advantage of indigenous energy resources such as solar power, wind, hydroelectric resources, land for bioenergy crops, CO_2 storage capability, or fossil resources to be used with CCS. Countries with less abundant resources may put greater emphasis on demand reductions and regional integration. Countries with resource bases that are easily tradeable, like low-carbon electricity or bioenergy, may choose to trade those resources rather than use them domestically (Box 6.10, Section 6.4.3, 6.4.5).

Regional Climate. Climate influences heating and cooling demand, both of which influence countries' energy demands and energy infrastructure to meet those demands (Section 6.5). In addition to daily demand profiles, heating and cooling are seasonal, influencing which energy sources may serve these loads and the seasonal storage they require. Cooling is almost entirely served by electricity today, and heating has commonly been served by non-electric fuels. In low-carbon energy systems, heating may be increasingly served by electricity (Section 6.6.4), meaning that the influence of regional climate may be strongest on countries' electricity systems.

Current Energy System Configuration. Future sectoral energy demands and the potential for demand-side transformation are partially determined by existing infrastructure (e.g., building stocks, transport infrastructure). Countries with less developed or growing energy systems will have more flexibility to create the systems that best match their long-term goals, but there may be substantial challenges in transitioning directly to the most advanced low-carbon technology options, and countries may have different capacities to absorb technology from other countries.

Regional Integration. Regional integration will allow countries to bridge energy gaps using external linkages, including regional electricity integration and trade in hydrogen, biomass, and other fuels. Countries with greater integration can rely more heavily on imports and may therefore rely less on indigenous resources (Box 6.10).

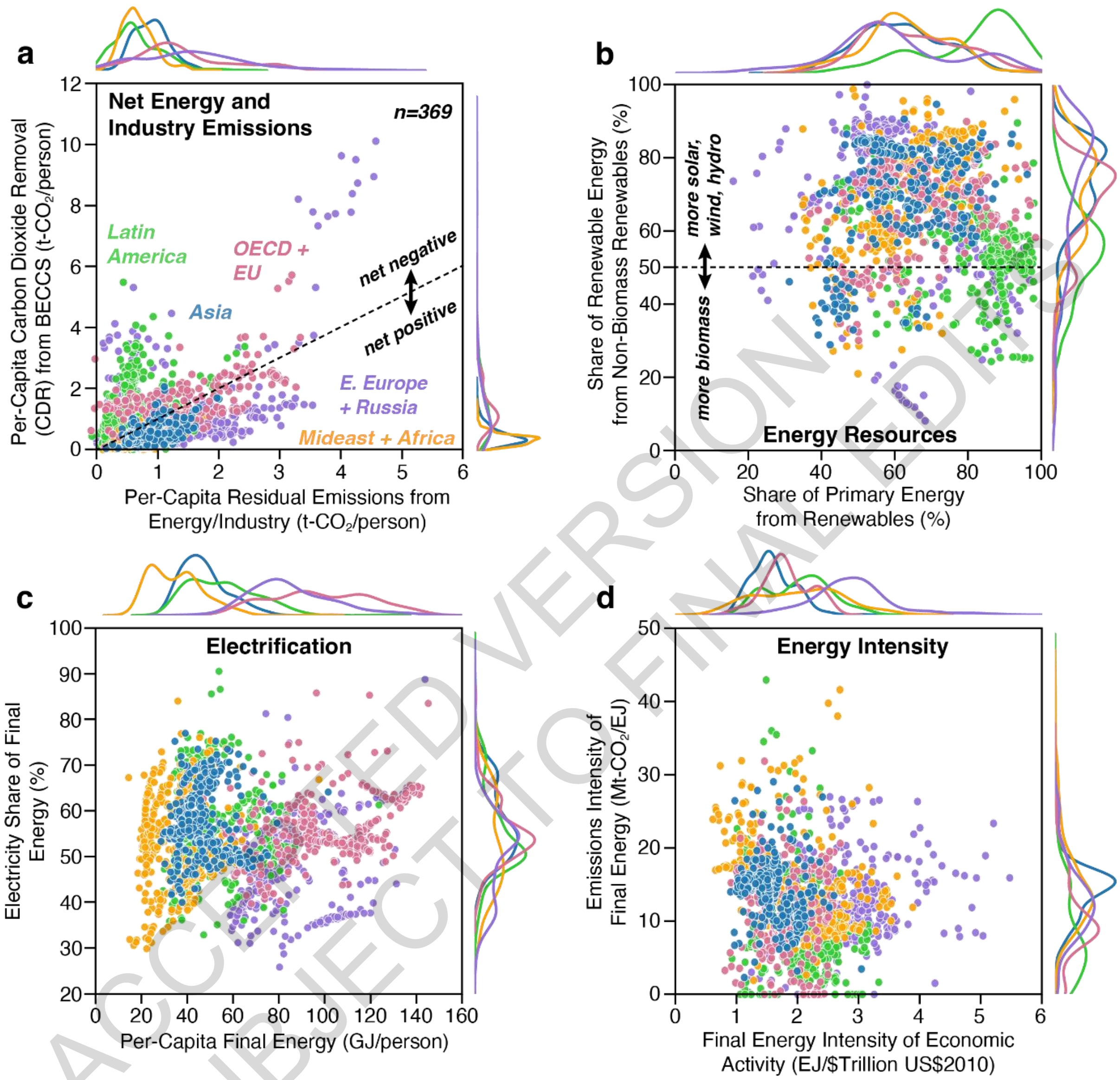


Figure 6.25 Characteristics of regional energy systems and emissions when energy and industrial CO_2 emissions reach net zero. Regional differences are shown for residual emissions and carbon removal (panel a), energy resources (panel b), electrification (panel c), and energy intensity (panel d). Distributions of scenarios are shown along each axis for each region. Colour scheme is shown in panel a. Points represent different models and scenarios from the AR6 database.

Societal Preferences. Citizens in every country have preferences for certain technological options or mitigation approaches over others that will influence energy system choices. The public generally prefers a future energy system based largely on renewables. Preferences for non-renewable energy differ across regions and groups. For example, studies have found that people in the U.K., Germany, the Netherlands, and Switzerland prefer renewable energy and personal energy efficiency and savings to nuclear, fossil fuels and CCS (Demski et al. 2017; Jones et al. 2012; Scheer et al. 2013; Volken et al. 2018; Bessette and Arvai 2018; Steg 2018). Studies have found that 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). The willingness to pay for renewable electricity differs by source (Ma et al. 2015; Sundt and Rehdanz 2015).

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

Energy Security. Countries emphasizing import security will tend to rely more heavily on indigenous resources (Section 6.3). Some indigenous resources may raise security of supply issues that will influence energy system configurations. Bioenergy and hydropower, for example, can be subject to import climate risks (6.5), and significant integration of VRE technologies will influence electricity system infrastructure and management (6.6.2, Box 6.8).

Other Factors. Countries will consider a wide range of other factors in building toward low-carbon energy systems. Population density, for example, will influence building and transportation energy demands; economic transitions will influence industrial energy demands. Societal priorities beyond climate, notably SDGs may influence technology choices and types of energy systems (Sections 6.3 and 6.7.7).

[START BOX 6.10 HERE]

Box 6.10 Regional Integration of Energy Systems

Energy systems are linked across countries in many ways: countries transport crude oil across the ocean in supertankers, pipelines carry oil and natural gas across country boundaries, electric power lines cross country boundaries, and countries trade industrial commodities that carry embodied energy or that are essential inputs to mitigation technologies. Future systems will generate electricity using different mixes of technologies, produce and transport different carriers (e.g., hydrogen or biofuels), and use far less fossil fuel, among other major changes. Important examples include electricity, hydrogen, and biomass.

Electricity System Integration. Net-zero energy systems will rely more heavily on electricity generated from low-emissions technologies. Given the significant variations in the location of low-carbon electricity resources and the temporal variability of some renewable electricity sources, notably solar and wind power, regional electricity grids could reduce overall costs of net zero energy systems (Section 6.4.5). Furthermore, electricity transmission interconnections could significantly reduce local energy balancing costs and investment in peaking plants needed to meet security of supply requirements, and it could increase system resilience, especially in the case of extreme events such as heat waves or cold spells (Fasihi and Bogdanov 2016). Important challenges to regional electricity integration include geopolitical concerns from cross-border trade and societal and technological challenges associated with building new transmission lines.

Hydrogen Trade. Hydrogen may play an important role in future net zero energy systems, particularly in applications where electricity is not economically advantageous (see Box 6.9). Hydrogen can be used to decarbonize regions in which it is produced, and it can also be transported long distances to facilitate decarbonization of sectors distant from sources of low-cost supply. Methods of long-distance, high-volume hydrogen transport could include liquid storage, chemical carriers, and gaseous delivery via pipelines (Section 6.4.5). In net zero systems with substantial wind and solar power generation, hydrogen can be generated through electrolysis and then shipped to other locations. Important challenges to hydrogen trade include cost-effective low carbon production, cost of delivery infrastructure, storage, and end-use technology costs and safety.

Trade in Biomass. Biomass may also play an important role in net zero energy systems (Section 6.6.4, Chapter 3). Large-scale bioenergy production and consumption is likely to trigger global biomass trade. Global bioenergy trade volumes presently exceed 1 EJ yr^{-1}, of which 60% is directly traded for energy purposes (Proskurina et al. 2019b). Established trade mechanisms include wood pellet transport, ethanol, and biodiesel (Proskurina et al. 2019a). In a net zero global energy system, bioenergy trade could be greater than current trade of coal or natural gas, but less than that of petroleum (Sharmina et al. 2017) (Mandley et al, 2020). Some studies indicate that Latin America and Africa could become key exporting regions, with the EU, the USA, and East Asia emerging as key importers (Rentizelas et al. 2019; Alsaleh and Abdul-Rahim 2018). Studies have found that net bioenergy exports could be as high as 10% of GDP for some Latin American countries, while other regions like the EU may be faced with burgeoning import reliance (Mahlknecht et al. 2020; Daioglou et al. 2020b). In addition to challenges associated with bioenergy production (Section 6.4, Chapter 7), important challenges to biomass trade include differences in sustainability criteria and land/biomass definitions in different jurisdictions, and difficulties in establishing consistent monitoring and auditing systems (Lamers et al, 2016).

[END BOX 6.10 HERE]

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

6.7.1 Low-Carbon Energy System Transition Pathways

6.7.1.1 Energy System Emissions

Without additional efforts to reduce emissions, it is very unlikely that energy system CO_2 emissions will decrease sufficiently to limit warming to well below 2°C (*high confidence*). Scenarios assuming improvements in technology but no additional climate policies beyond those in place today provide a benchmark for comparison against energy-related CO_2 emissions in mitigation scenarios (Figure 6.26). Emissions in these reference scenarios increase through 2050 but span a broad range (Chapter 3 Figure 3.16; Riahi et al. 2017; Wei et al. 2018). The highest emissions levels are about four times current emissions; the lowest are modestly below today's emissions. Emissions in these scenarios increase in most regions, but they diverge significantly across regions (Bauer et al. 2017). Asia and the Middle East and Africa account for the majority of increased emissions across these scenarios (Figure 6.27). While it is unlikely that there will be no new climate policies in the future, these scenarios nonetheless support the conclusion that the energy sector will not be decarbonized without explicit policy actions to reduce emissions.

Warming cannot be limited to well below 2°C without rapid and deep reductions in energy system GHG emissions (*high confidence*). Energy sector CO_2 emissions fall by 87-97% (interquartile range) by 2050 in scenarios limiting warming to 1.5°C with no or limited overshoot and 60-79% in scenarios limiting likely warming to 2°C (Figure 6.26). Energy sector GHG emissions fall by 85-95% (interquartile range) in scenarios limiting warming to 1.5°C with no or limited overshoot and 62-78% in scenarios limiting likely warming to 2°C (Figure 6.26). In 2030, in scenarios limiting warming to 1.5°C with no or limited overshoot, net CO2 and GHG emissions fall by 35-51% and 38-52% respectively. Key characteristics of emissions pathways – the year of peak emissions, the year when net emissions reach zero, and the pace of emissions reductions – vary widely across countries and regions. These differences arise from differences in economic development, demographics, resource endowments, land use, and potential carbon sinks (Schreyer et al. 2020)(Schaeffer, et al.2020; Schreyer, et al., 2020; van Soest, Heleen, et al., 2021;Figure 6.27, Figure 6.28, Box 6.11). If countries do not move quickly to reduce emissions – if reductions are delayed – a more rapid energy transition will subsequently be required to limit warming to 2°C or below (Rogelj et al. 2015a, 2018a; IPCC 2018).

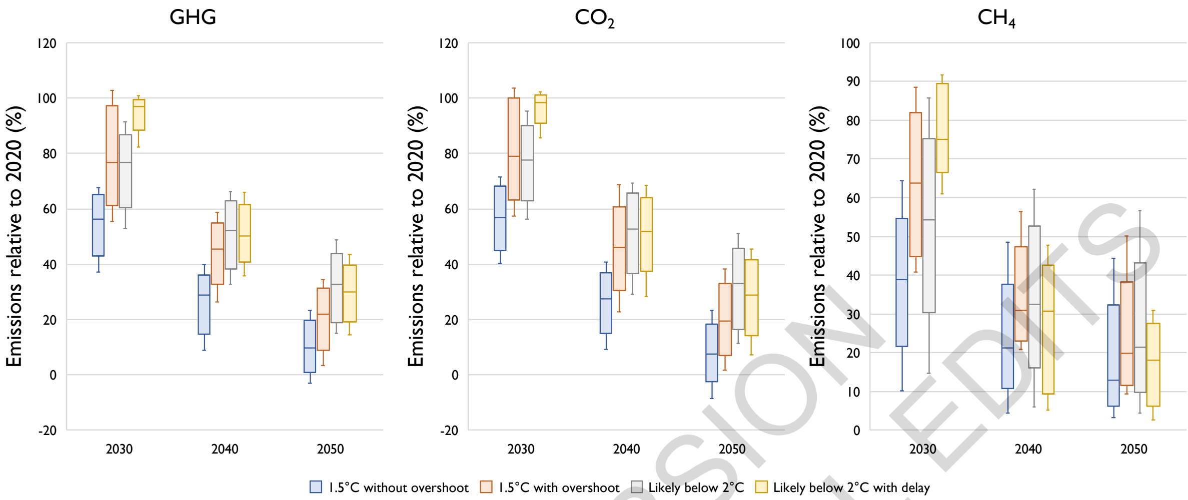


Figure 6.26 Projected energy sector GHG emissions for the 1.5°C scenarios (without and with overshoot), and likely below 2°C scenarios (without and with delayed policy action) during 2020-2050 (Source: AR6 Scenario Database). Boxes indicate 25th and 75th percentiles while whiskers indicate 5th and 95th percentiles. GHG emissions are inclusive of energy sector CO_2, CH_4, N_2O emissions and 80% of global HFC emissions. Number of model-scenario combinations in AR6 database: 1.5°C without overshoot: 170, 1.5°C with overshoot: 177, 2°C without delay: 297, 2°C without delay: 124.

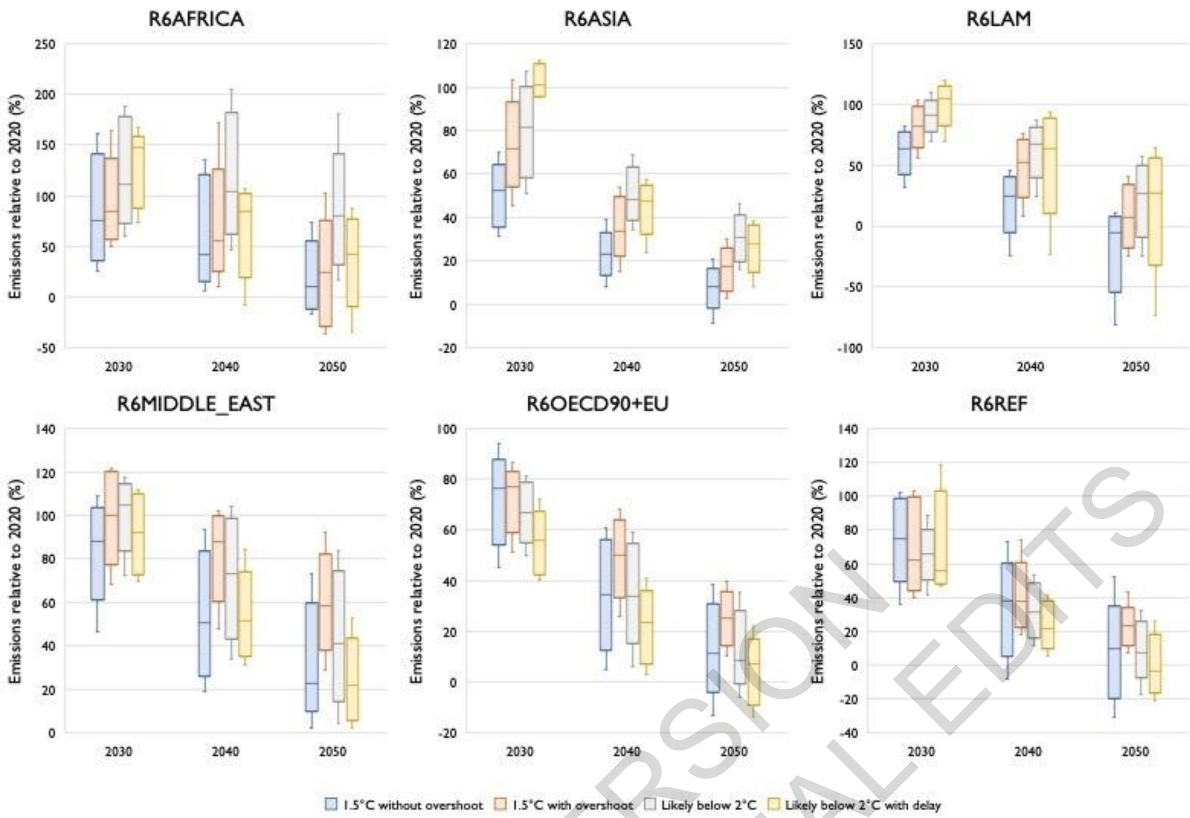


Figure 6.27 Net regional (R5) CO_2 emissions from energy across scenarios. for the 1.5°C scenarios (without and with overshoot), and likely below 2°C scenarios (without and with delayed policy action) during 2020-2050 (Source: AR6 Scenario Database). Boxes indicate 25th and 75th percentiles while whiskers indicate 5th and 95th percentiles. Most mitigation scenarios are based on a cost-minimizing framework that does not consider historical responsibility or other equity approaches.

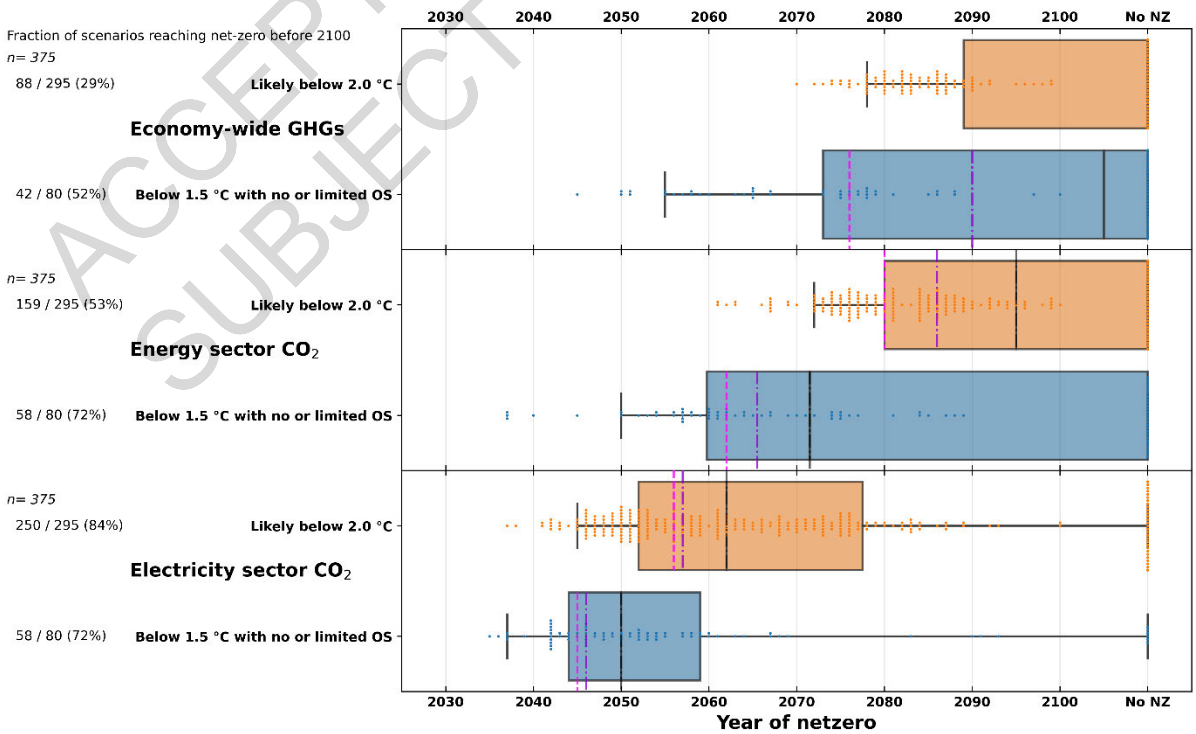


Figure 6.28 The timing of net zero emissions for full economy GHGs, energy sector CO_2, and electricity sector CO_2. Boxes indicate 25th and 75th percentiles, centre black line is the median, while whiskers indicate 1.5x the inter-quartile range. The vertical dashed lines represent the median point at which emissions in the scenarios have dropped by 95% (pink) and 97.5% (purple), respectively. Dots represent individual scenarios. The fraction indicates the number of scenarios reaching net zero by 2100 out of the total sample. (Source: AR6 Scenario Database)

The timing of net zero energy system emissions varies substantially across scenarios. In scenarios limiting warming to 1.5°C with no or limited overshoot (likely below 2°C), the energy system reaches net zero CO_2 emissions (interquartile range) from 2060 onwards (2080-). (Figure 6.28). However, net emissions reach near-zero more quickly. For example, in scenarios limiting warming to 1.5C with no or limited overshoot (likely below 2C) net energy system CO_2 emissions drop by 95% between 2056 and 2075 (2073 and 2093). Net full economy GHG emissions reach zero more slowly than net CO_2 emissions. In some scenarios, net energy system CO_2 and total GHG emissions do not reach zero this century, offset by CDR in other sectors.

The timing of emissions reductions will vary across the different parts of the energy sector (Figure 6.28). To decarbonize most cost-effectively, global net CO_2 emissions from electricity generation will likely reach zero before the rest of the energy sector (*medium confidence*). In scenarios limiting warming to 1.5C with no or limited overshoot (likely below 2C), net electricity sector CO_2 emissions (interquartile range) reach zero globally between 2044 and 2055 (2052 and 2078) (Figure 6.28). It is likely to be less-costly to reduce net CO_2 emissions close to or below zero in the electricity sector than in other sectors, because there are relatively more low-emissions options in electricity. Sectors such as long-distance transport, air transport, and process heat are anticipated to face greater challenges to decarbonization than the electricity sector (Rogelj et al. 2018b, 2015b; Clark and Herzog 2014; IPCC 2018; Luderer et al. 2018).

In addition, there are potential options to remove CO_2 from the atmosphere in the electricity sector, notably BECCS, which would allow electricity sector emissions to drop below zero. Without CDR options, electricity sector emissions may not fall all the way to zero. If CDR is accomplished in other sectors and not in electricity, some fossil fuel plants may still lead to positive net electricity sector CO_2 emissions even in net zero economies (Williams et al. 2021a; Bistline and Blanford 2021b)

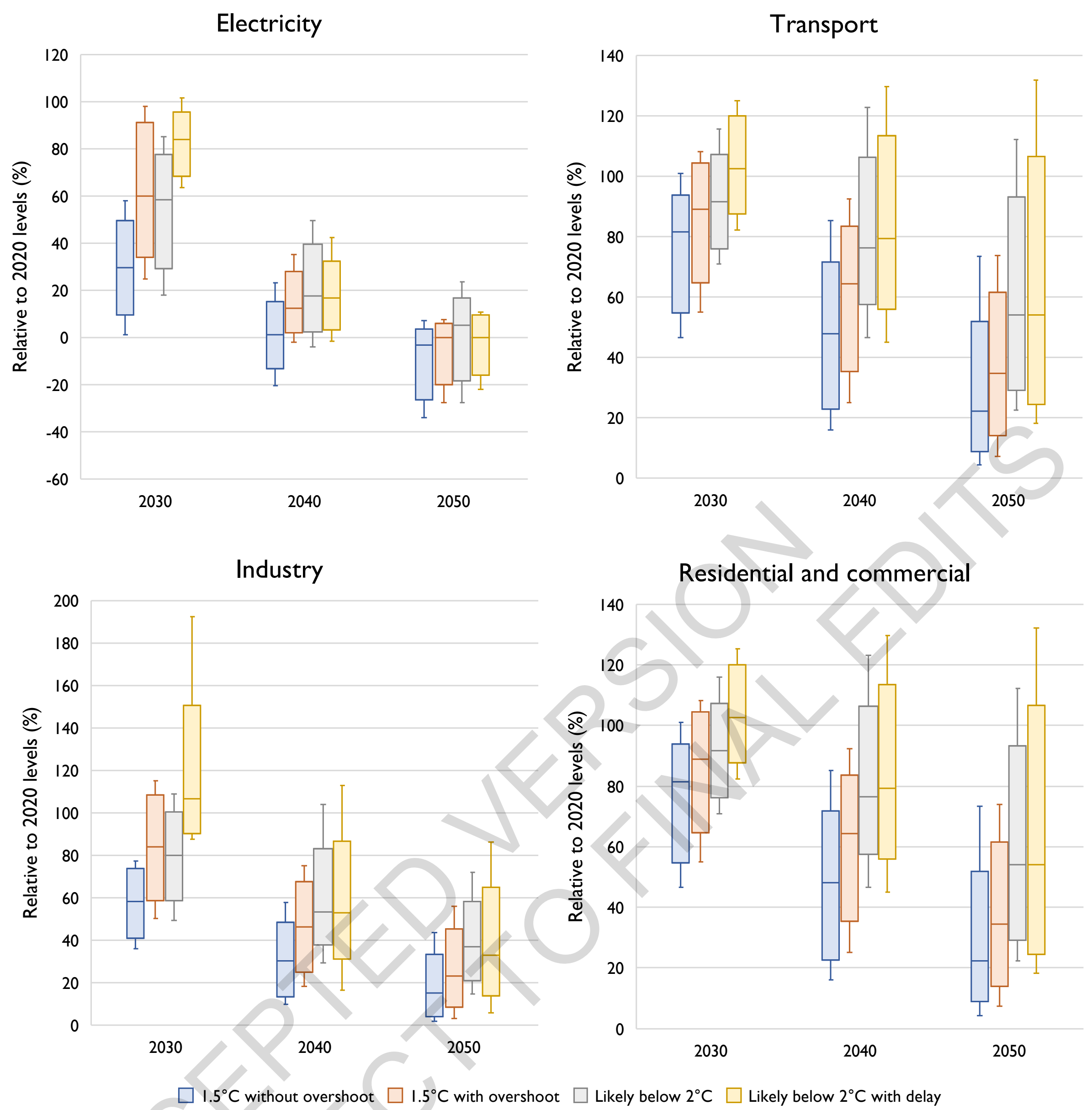


Figure 6.29 Reductions in CO_2 emissions relative to 2020 levels for the 1.5°C scenarios (without and with overshoot), and likely below 2°C scenarios (without and with delayed policy action) during 2030-2050 (Source: AR6 Scenario Database). Boxes indicate 25th and 75th percentiles while whiskers indicate 5th and 95th percentiles.

We lack sufficient understanding to pin down precise dates at which energy system CO_2 emissions in individual countries, regions, or sectors will reach net zero. Net-zero timing is based on many factors that are not known today or are bound up in development of key technologies, such as energy storage, bioenergy, or hydrogen. Some countries have low-carbon resource bases that could support deep emissions reductions, while others do not. Timing is also affected by the availability of CDR options, whether these options are in the energy sector or elsewhere, and the discount rate used to assess strategies (Bednar et al. 2019; Emmerling et al. 2019). Moreover, while many scenarios are designed to minimize global mitigation costs, many other frameworks exist for allocating mitigation effort across countries (Chapter 4; van den Berg, N. J., et al., 2019).

6.7.1.2 Low-carbon energy transition strategies

There are multiple technological routes to reduce energy system emissions (see Section 6.6). Here we discuss three of these: (1) decarbonizing primary energy and electricity generation, (2) switching to electricity, bioenergy, hydrogen, and other fuels produced from low-carbon sources, and (3) limiting energy use through improvement of efficiency and conservation. CDR is discussed in Section 6.7.1.X; Fossil fuel transitions are discussed in Section 6.7.4.

Decarbonizing Primary Energy and Electricity Generation. Limiting warming to well below 2°C requires a rapid and dramatic increase in energy produced from low- or zero-carbon sources *(high confidence)*. Low- and zero-carbon technologies produce 74-82% (interquartile range) of primary energy in 2050 in scenarios limiting warming to 1.5°C with no or limited overshoot and 55-68% in likely below 2°C scenarios (Figure 6.29). The share of low-carbon technologies in global primary energy supply today is below 20% (Section 6.3, Chapter 3,Figure 6.29). The percentage of low- and zero-carbon energy will depend in part on the evolution of energy demand – the more that energy demand grows, the more energy from low- and zero-carbon sources will be needed and the higher the percentage of total primary energy these sources will represent.

Low- and zero-carbon sources produce 97-99% of global electricity in 2050 in scenarios limiting warming to 1.5°C with no or limited overshoot and 93-97% in likely below 2°C scenarios (Figure 6.29) (*medium confidence*). Decarbonizing electricity generation, in tandem with increasing use of electricity (see below), is an essential near-term strategy for limiting warming. The increase in low- and zero-carbon electricity will occur while electricity demand grows substantially. Studies have projected that global electricity demand will roughly double by 2050 and quadruple to quintuple by 2100 irrespective of efforts to reduce emissions (Bauer et al. 2017; Luderer et al. 2017; IEA 2019a).

Renewable energy, especially generation from solar and wind, is likely to have an important role in many low-carbon electricity systems. The contributions of wind and solar electricity will depend on their levelized costs relative to other options, integration costs, system value, and the ability to integrate variable resources into the grid (Section 6.6). Electric sector technology mixes will vary by region but will typically include additional resources such as hydropower, nuclear power, fossil generation with CCS, energy storage resources, and geothermal energy, among others. Contributions of different options vary widely across scenarios based on different assumptions about these factors (Figure 6.30).

Nonetheless, it is likely that wind and solar will dominate low-carbon generation and capacity growth over the next couple decades due to supporting policies in many countries and due to their significant roles in early electric sector decarbonization, alongside reductions in coal generation (Bistline and Blanford 2021b; Pan et al. 2021). Clean firm technologies play important roles in providing flexibility and on-demand generation for longer durations, though deployment of these technologies is typically associated with deeper decarbonization levels (e.g., beyond 70-80% reductions), which are likely to be more important after 2030 in many regions, and with more limited CDR deployment (Baik et al. 2021; Williams et al. 2021a; Bistline and Blanford 2021a).

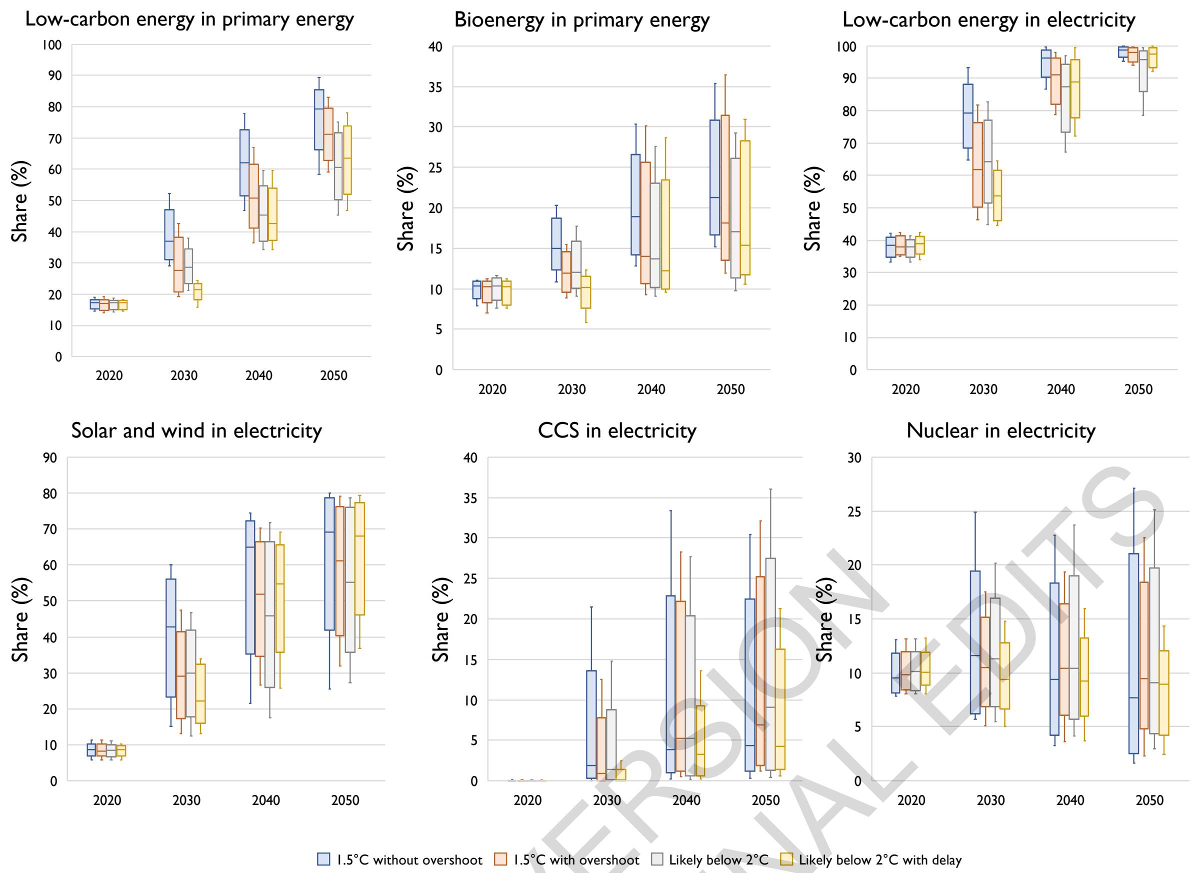
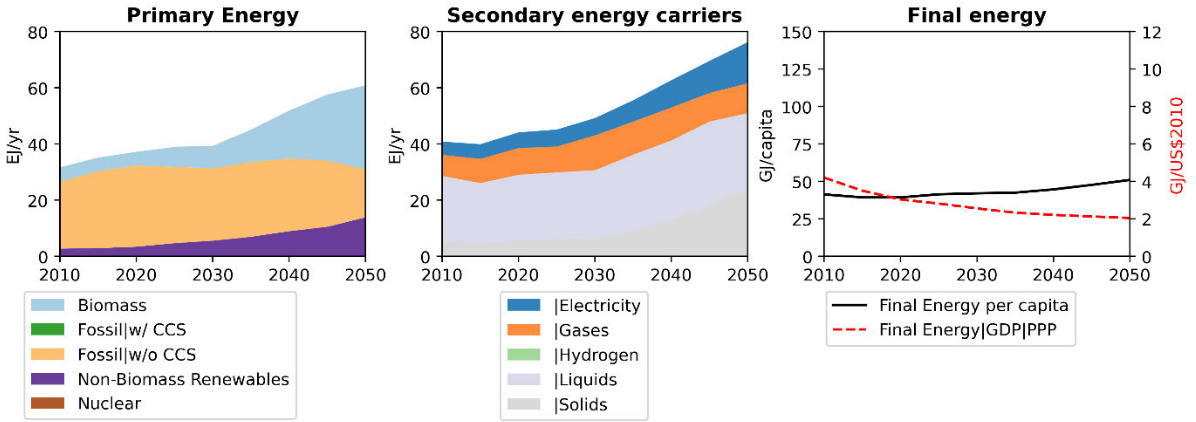


Figure 6.30 Shares of low carbon energy (all sources except unabated fossil fuels) and bioenergy (including both traditional and commercial biomass) in total primary energy, and solar+wind, CCS and nuclear in electricity for the 1.5°C scenarios (without and with overshoot), and likely below 2°C scenarios (without and with delayed policy action) during 2020-2050 (Source: AR6 Scenario Database). Boxes indicate 25th and 75th percentiles while whiskers indicate 5th and 95th percentiles.

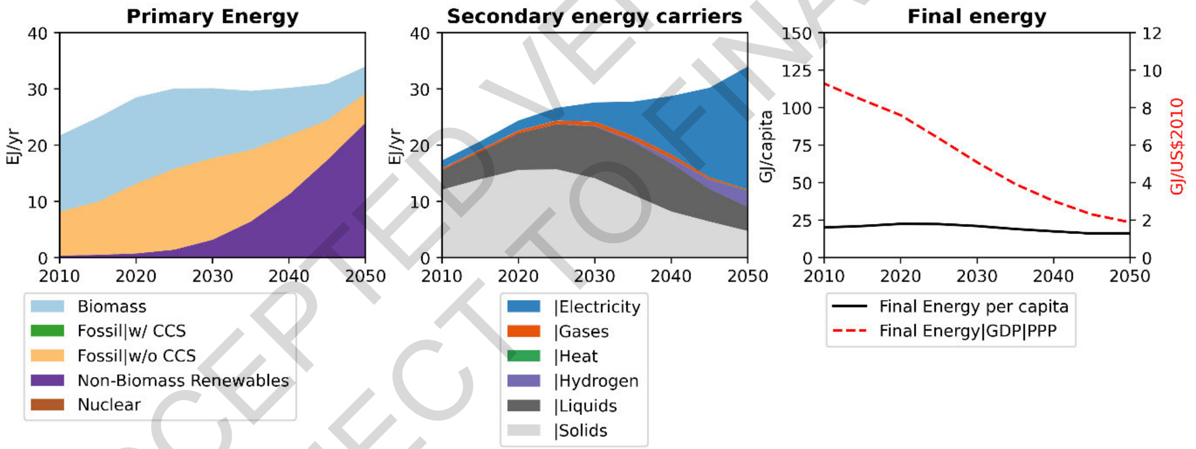
[START BOX 6.11 HERE]

Box 6.11 Illustrative Low-Carbon Energy System Transitions

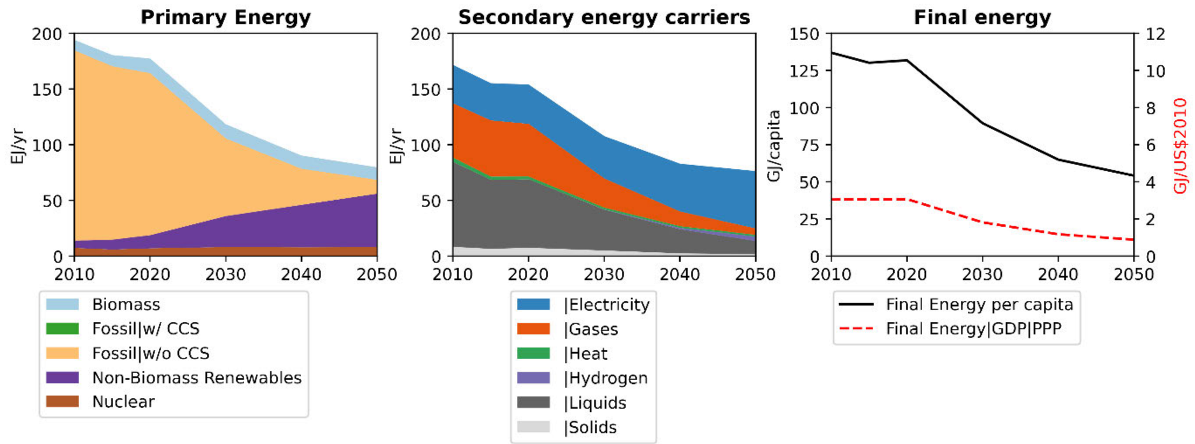
There are multiple possible strategies to transform the energy system to reach net zero CO_2 emissions and to limit likely warming to 2°C or below. All pathways rely on the strategies for net zero CO_2 energy systems highlighted in Section 6.6.2, but they vary in the emphasis that they put on different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



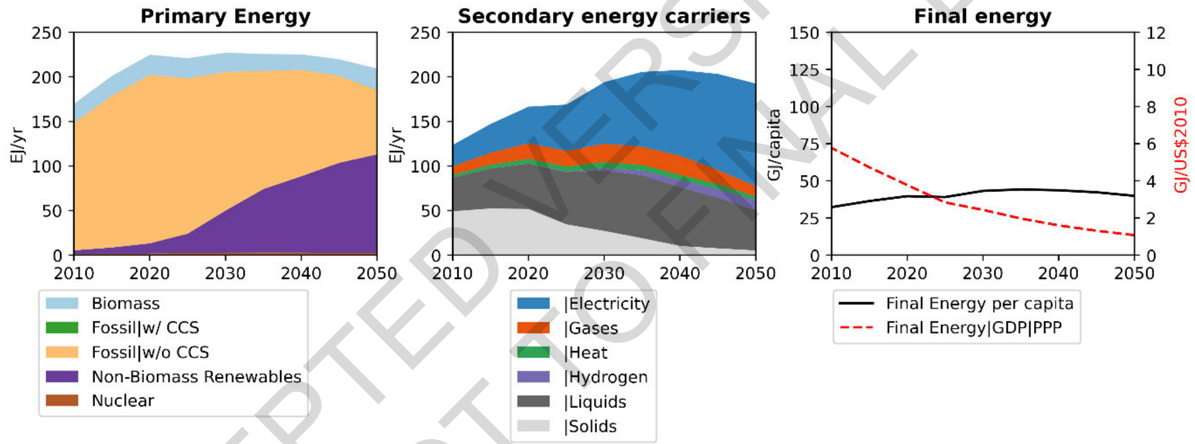
Box 6.11, Figure 1 Illustrative Mitigation Pathway 2.0-Neg: Latin America & Caribbean (LAM) in a likely below 2°C scenario (LAM net-zero economy 2040-2045, net zero energy system 2045-2050). Supply side focus with growing dependency on carbon dioxide removal and AFOLU, thus achieves net-zero CO_2 relatively early.



Box 6.11, Figure 2 Illustrative Mitigation Pathway 1.5-Renewables: Africa (AF) in a 1.5°C scenario (AF net-zero economy, 2055-2060, AF net zero energy system 2055-2060). Rapid expansion of non-biomass renewables, high electrification, and a fossil fuel phaseout.



Box 6.11, Figure 3 Illustrative Mitigation Pathway 1.5-Low Demand: Developed Countries (DEV) in a 1.5°C scenario (DEV net-zero economy, 2055-2060, net zero energy system 2075-2080). Major reduction of energy demand, high electrification, and gradual fossil fuel phaseout.



Box 6.11, Figure 4 Illustrative Mitigation Pathway 1.5-Shifting Pathways: Asia and Developing Pacific (APC) in a 1.5°C scenario (APC net-zero economy, 2075-2080, net-zero energy system 2090-2095). Renewables, high electrification, fossil fuel phaseout and low AFOLU emissions. Reaches net-zero CO_2 relatively late.

Box 6.11, Table 1. Summary of selected Illustrative Mitigation Pathways energy system characteristics in 2050 for the chosen regions.

		Energy sector CO_2 Reduction 2020-2050	Energy intensity	Variable renewable electricity generation	Low carbon electricity capacity additions	CO_2 Removal BECCS, AFOLU, Total	GDP per capita	Year net-zero CO2 emissions

		%	MJ / PPP USD2010		EJ/yr (%)		GW/yr		Gt CO_2 yr^{-1}	PPP USD2010/person		Full economy	Energy sector	Electricity
	Region	2050	2020	2050	2020	2050	2020	2050	2050	2020	2050			
Neg	LAM	124	3	2.1	0.5 (9)	7.7 (53)	15.4	21.5	1.1, 0.2, 1.9	12952	24860	2040-2045	2045-2050	2025-2030
Ren	AF	85	7.6	1.9	0.1 (5)	18 (84)	5	217	0.1, 0, 0.1	2965	8521	2055-2060	2055-2060	2025-2030
LD	DEV	92	3.1	0.9	4.6 (13)	37 (72)	52	188	0, 0.6, 0.6	42945	61291	2055-2060	2075-2080	2045-2050
SP	APC	76	3.8	1.1	3 (7)	91 (79)	123	603	0.1, 0.4, 0.4	10514	37180	2075-2080	2085-2090	2085-2090

[END BOX 6.11 HERE]

Switching to Low-Carbon Energy Carriers. Switching to energy carriers produced from low-carbon sources will be an important strategy for energy sector decarbonization. Accelerated electrification of end uses such as light duty transport, space heating, and cooking is a critical near-term mitigation strategy (Waisman et al. 2019; Sugiyama 2012; Zou et al. 2015; Rockström et al. 2017; IEA 2019f; Tang et al. 2021a). Electricity supplies 48-58% (interquartile range) of the global final energy demand by 2050 in scenarios limiting warming to 1.5°C with no or limited overshoot and 36-47% in likely below 2°C scenarios (Figure 6.29). Globally, the current level of electrification is about 20%.

Indirect electrification encompasses the use of electricity to produce hydrogen and synthetic fuels (efuels or power fuels). The extent of indirect electrification of final energy will depend on resource endowments and other regionally specific circumstances. Although indirect electrification is less efficient compared to direct electrification, it allows low-carbon fuels to be imported from regions with abundant low carbon electricity generation resources (Fasihi and Breyer 2020; Fasihi and Bogdanov 2016; Lehtveer et al. 2019, Box 6.10 on regional integration).

While electrifying end uses is a key decarbonization strategy, some end uses such as long-distance transport (freight, aviation, and shipping) and energy-intensive industries will be harder to electrify. For these sectors, alternative fuels or energy carriers such as biofuels, hydrogen, ammonia or synthetic methane, may be needed (see Section 6.6 and Box 6.9). Most scenarios find that hydrogen consumption will grow gradually, becoming more valuable when the energy system has become predominantly low-carbon (Figure 6.31).

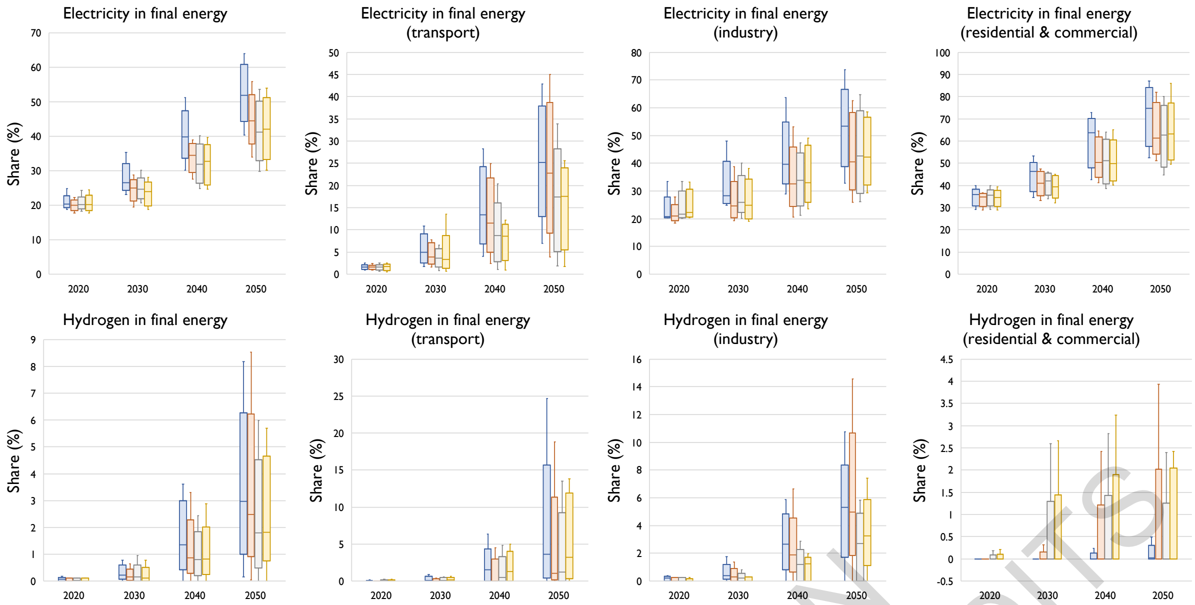


Figure 6.31 Shares of electricity and hydrogen in final energy for scenarios limiting warming to 1.5°C scenarios (without and with overshoot) and scenarios limiting likely warming to below 2°C (without and with delayed policy action) during 2020-2050 (Source: AR6 Scenario Database). Boxes indicate 25th and 75th percentiles while whiskers indicate 5th and 95th percentiles.

Reducing Energy Demand. Energy service demand is expected to continue to increase with growth of the economy, but there is great uncertainty about how much it will increase (Riahi et al. 2017; Bauer et al. 2017; Yu et al. 2018). Given the need to produce low-carbon energy, the scale of energy demand is a critical determinant of the mitigation challenge (Riahi et al. 2012). Higher energy demand calls for more low-carbon energy and increases the challenge; lower energy demand reduces the need for low-carbon sources and therefore can ease a low-carbon transtion. Recent studies have shown that tempering the growth of energy demand, while ensuring services and needs are still satisfied, can materially affect the need for technological CDR (see below) (Grubler et al. 2018; van Vuuren et al. 2018). Two of the Illustrative Mitigation Pathways (IMP-SP, IMP-LD) feature substantially lower final energy demand across buildings, transport, and industry than most other pathways in the literature. In some cases, energy demand levels are lower in 2050 (and later) than in 2019. These lower demands result in less reliance on bioenergy and a more limited role for CDR. [Ch. 3, Figure 3.18]

6.7.1.3 Technology options to offset residual emissions

CDR technologies can offset emissions from sectors that are difficult to decarbonize (Section 6.6), altering the timeline and character of energy sector transitions. A number of studies suggest that CDR is no longer a choice but rather a necessity to limit warming to 1.5°C (Luderer et al. 2018; Rogelj et al. 2015a; van Vuuren et al. 2018; Detz et al. 2018; Strefler et al. 2018). The reliance on CDR varies across scenarios and is tightly linked future energy demand and the rate of emission reductions in the next two decades: deeper near-term emissions reductions will reduce the need to rely on CDR to constrain cumulative CO_2 emissions. Some studies have argued that only with a transition to lower energy demands will it be possible to largely eliminate the need for engineered CDR options (Grubler et al. 2018; van Vuuren et al. 2018). Overall, the amount of CDR will depend on CO_2 capture costs, lifestyle changes, reduction in non-CO_2 GHGs, and utilization of zero-emission end-use fuels (van Vuuren et al. 2018)(Muratori et al, 2017; van Vuuren et al, 2018).

There is substantial uncertainty about the amount of CDR that might ultimately be deployed. In most scenarios that limit warming to 1.5°C, CDR deployment is fairly limited through 2030 at less than 1 Gt-CO_2 yr^{-1}. The key projected increase in CDR deployment (BECCS and DAC only) occurs between

2030 and 2050 with annual CDR in 2050 projected at 2.5-7.5 Gt-CO_2 yr^{-1} in 2050 (interquartile range) in scenarios limiting warming to 1.5°C with limited or no overshoot and 0.7-1.4 Gt-CO_2 yr^{-1} in 2050 in scenarios limiting warming to 2°C with limited or no overshoot. This characteristic of scenarios largely reflects substantial capacity addition of BECCS power plants. BECCS is also deployed in multiple ways across sectors. For instance, the contribution (interquartile range) of BECCS to electricity is 1-5% in 2050 in scenarios limiting warming to 1.5°C with limited or no overshoot and 0-5% in scenarios limiting likely warming to below 2°C . The contribution (interquartile range) of BECCS to liquid fuels is 9-21% in 2050 in scenarios limiting warming to 1.5°C with limited or no overshoot and 2-11% in scenarios limiting likely warming to below 2°C. Large-scale deployment of CDR allows flexibility in timing of emissions reduction in hard-to-decarbonize sectors.

CDR will influence the potential fossil-related stranded assets (Box 6.13). Availability of low-cost CDR can help reduce premature retirement for some fossil fuel infrastructure. CDR can allow countries to reach net zero emissions without phasing out all fossil fuels. Specific infrastructure could also be extended if it is used to burn biomass or other non-emitting sources. For example, existing coal-fired power plants, particularly those with CCS, could be co-fired with biomass (Pradhan et al, 2021; Woolf et al, 2016; Lu et al, 2019). In many scenarios, energy sector CDR is deployed to such an extent that energy sector CO_2 emissions become negative in the second half of the century (Chapter 3).

[START BOX 6.12 HERE]

Box 6.12 Taking Stock of the Energy System Transition

The Global Stocktake is a regularly occurring process under the UNFCCC in which efforts will be made to understand progress on, among other things, global mitigation. Collective progress of countries towards the Paris Agreement goal will be assessed and its outcome will inform Parties in updating and enhancing their NDCs. This box explores potential indicators to understand energy system mitigation progress.

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

Beyond these aggregate indicators, a second order assessment would capture more details, such as the electrification rate, share of renewables, nuclear, CCS or other low carbon technologies in electricity generation, land area used for energy production, and numbers of EV or PHEV. Consumption of coal, oil and gas captures the underlying factors of CO_2 emissions. The emphasis of these indicators could differ across countries in the context of national specific circumstances. Technology- or project-based statistics are also useful to check the progress of the low-carbon transition, for example, the number of CCS facilities.

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

[END BOX 6.12 HERE]

6.7.2. Investments in Technology and Infrastructure

Total global energy investment was roughly USD 1940 billion yr^{-1} in 2019 (IEA 2021f). This total can be broken down into the following main categories: fossil-related energy supply, including oil, gas, and coal extraction and fossil electricity generation (USD 990 billion yr^{-1}); renewable electricity, primarily solar and wind (USD 340 billion yr^{-1}); nuclear energy (USD 40 billion yr^{-1}); electricity networks (USD 270 billion yr^{-1}); and end-use energy efficiency (USD 270 billion yr^{-1}).

Energy investment needs are projected to rise going forward, according to investment-focused scenario studies found in the literature (Bertram et al. 2021; McCollum et al. 2018a; Zhou et al. 2019). While these increases are projected to occur in emissions-intensive pathways as well as low-carbon pathways, they are projected to be largest in low-carbon pathways. Average annual global energy investments over the 2016-2050 period range (across six models) from USD 2100 to 4100 billion yr^{-1} in pathways likely limiting warming to 2°C and from USD 2400 to 4700 billion yr^{-1} in pathways limiting warming to 1.5°C with no or limited overshoot (McCollum et al., 2018). Whatever the scenario, a significant and growing share of investments between now and 2050 will be channelled toward infrastructure build-out in emerging economies, particularly in Asia (Zhou et al. 2019).

More widespread electrification of buildings, transport, and industry means particularly substantial investment in the electricity system. According to C1-C3 pathways in the AR6 scenario database, such investments could be at the following average annual levels (inter-quartile range, USD_{2015}) over the 2023-2052 timeframe: USD 1670 to 3070 billion yr^{-1} (C1), 1600 to 2780 billion yr^{-1} (C2), and 1330-2680 billion yr^{-1} (C3). (See also 3.6.1.3)

Beyond these sector-wide numbers, a key feature of stringent mitigation pathways is a pronounced reallocation of investment flows across sub-sectors, namely from unabated fossil fuels (extraction, conversion, and electricity generation) and toward renewables, nuclear power, CCS, electricity networks and storage, and end-use energy efficiency (McCollum et al. 2018a; Bertram et al. 2021; IEA 2021f) (Figure 6.32). Investments in solar, wind, and electricity transmission, distribution, and storage increase the most in mitigation scenarios. Up to 2050, the bulk of these investments are made in OECD and Asian countries (Figure 6.33). While fossil fuel extraction investments exhibit a marked downscaling across all regions, compared to reference scenarios, the declines are especially strong in the Middle East, REF, and OECD.

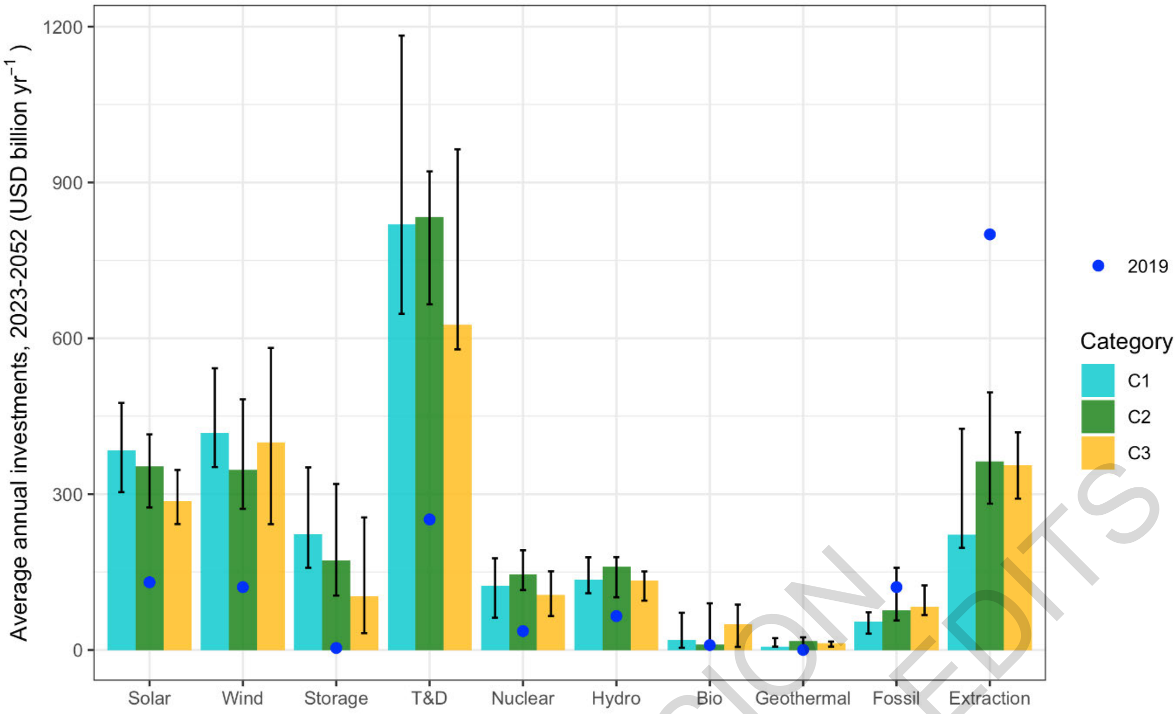


Figure 6.32 Global average annual investments from 2023 to 2052 (undiscounted, in USD billion yr^{-1}) for electricity supply sub-sectors and for extraction of fossil fuels in C1-C3 pathways (Source: AR6 Scenario Database and Chapter 3). Historical investments are also shown for comparison (Source: IEA, 2021; approximations are made for hydro and geothermal based on available data; solar and wind values are for 2020). 'T&D': transmission and distribution of electricity. Bars show median values across models-scenarios, and whiskers the inter-quartile ranges. See Chapters 3 and 15 for additional information on investments and finance.

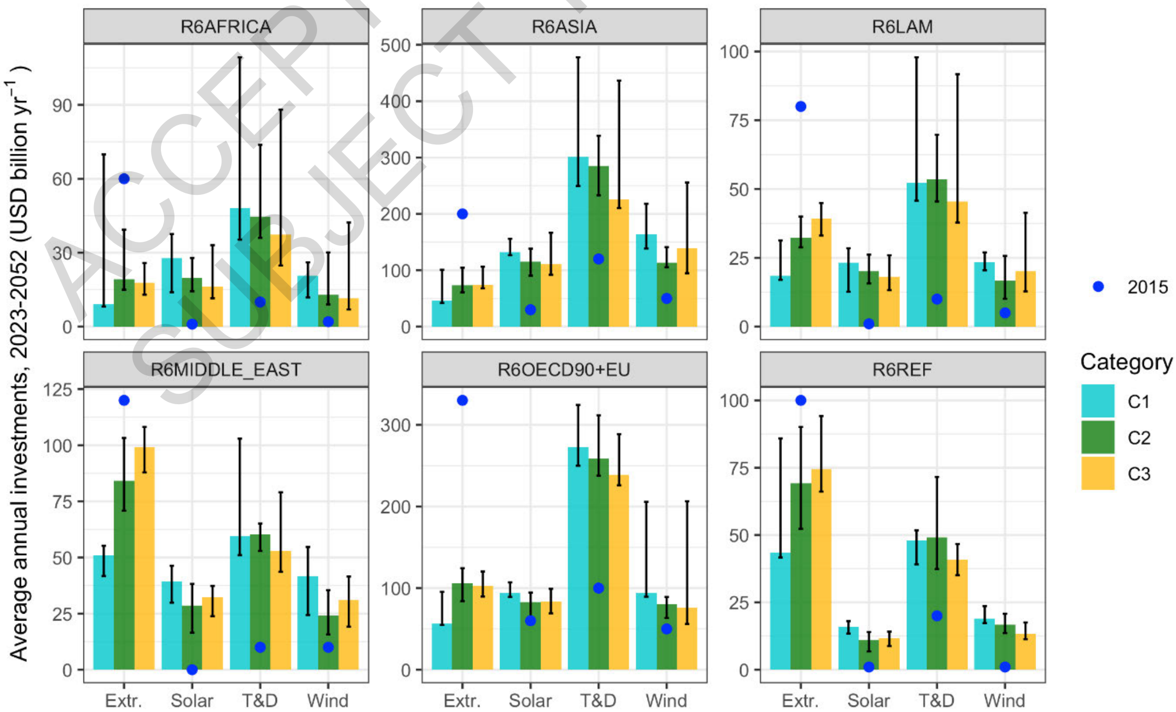


Figure 6.33 Regional average annual investments from 2023 to 2052 (undiscounted, in USD billion yr^{-1}) for four of the largest sub-sectors of the energy system in C1-C3 pathways (Source: AR6 Scenario Database and Chapter 3). Historical investments are also shown for comparison (Source: IEA, 2016). 'T&D': transmission and distribution of electricity. 'Extr.': extraction of fossil fuels. Bars show median values across models-scenarios, and whiskers the inter-quartile ranges. See Chapters 3 and 15 for additional information on investments and finance.

Investments into end-use energy efficiency are projected to also be substantial in mitigation pathways, potentially upwards of several hundred USD billion yr^{-1} on average to 2050, compared to USD 270 billion yr^{-1} in 2019 (McCollum et al. 2018a; IEA 2021f). However, the literature is inconsistent in how demand-side investments are calculated, as boundary conditions are less clear than for energy supply investments. Taking a broader definition can result in estimates that are an order-of-magnitude higher, meaning as large or larger than supply-side investments (IEA 2021f; Grubler et al. 2012).

Increasing low-carbon investment primarily requires shifting existing capital investment through regulation and incentives as well as removing existing investment barriers (McCollum et al. 2018a)(Ameli, N. et al., 2021: Hafner et al. 2020: McCollum et al. 2018). While there is a considerable amount of capital in the world, it is not always available to those wishing to invest in certain projects. Total annual global investment in fixed capital was USD 22.4 trillion in 2021, over an order-of-magnitude larger than energy sector investment (World Bank, 2021).

Future investment patterns will vary by region, as they do now, due to differences in risk profiles, resource endowments and economic and governance structures (Zhou et al. 2019)(6.6; Ameli, N. et al., 2021; Fizaine et al. 2016; Zhou et al., 2019). In rapidly growing countries, investments to support a low-carbon energy system transition will be integrated with those needed to meet rapidly increasing energy demands, irrespective of whether efforts are made to reduce emissions. In less-rapidly-growing countries (Sun et al. 2019), investments will focus on transitioning current energy systems to low-carbon configurations. Most current energy investments are concentrated in high- and upper-middle income countries (IEA 2021f), but this will change as investment needs continue to grow in today's lower-middle and low-income countries (Bertram et al. 2021; McCollum et al. 2018a; Zhou et al. 2019; IEA 2021f).

6.7.3 Energy System Lock-In and Path Dependence

Path dependence refers to resistance to change due to favourable socio-economic conditions with existing systems; decisions made in the past unduly shape future trajectories. Carbon lock-in is a specific type of path dependence (Seto et al. 2016). Given that energy system mitigation will require a major course change from recent history, lock-in is an important issue for emission reductions in the energy sector. While lock-in is typically expressed in terms of physical infrastructure that would need to be retired early to reach mitigation goals, it involves a much broader set of issues that go beyond physical systems and into societal and institutional systems (Table 6.11).

Table 6.11 Lock-in types and typical mechanisms (Kotilainen et al. 2020). Reproduced under Creative Commons 4.0 International License.

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

6.7.3.1 Societal and Institutional Inertia

A combination of factors - user, business, cultural, regulatory, and transnational - will hinder low-carbon energy transitions. Strong path dependencies, even in early formative stages, can have lasting impacts on energy systems, producing inertia that cuts across technological, economic, institutional and political dimensions (*high confidence*) (Vadén et al. 2019; Rickards et al. 2014) Chapter 5).

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

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

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

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

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

6.7.3.2 Physical Energy System Lock-In

Current investments in fossil infrastructure have committed 500-700 Gt-CO_2 of emissions, creating significant risks for limiting warming to 1.5°C (Callaghan 2020) (*high confidence*). These current investments combined with emissions from proposed fossil infrastructure exceed the emissions required to limit warming to 1.5°C (*medium confidence*). Existing coal and gas fired electricity generation accounts for 200-300 Gt-CO_2 of committed emissions. Emissions from coal generation are larger than for gas plants (Tong et al. 2019; Smith et al. 2019). The lifetime of coal-fired power plants is 25-50 years, creating long lasting risks to climate goals (Erickson and Tempest 2015). Gas-fired power plants are generally younger than coal-fired power plants. Industry sector lock-in amounts for more than 100 Gt-CO_2, while buildings and transport sector together contribute another 50-100 Gt-CO_2 (Erickson and Tempest 2015).

Lock-in is also relevant to fossil resources. Both coal and gas exploration continue, and new permits are being issued, which may cause economic (Erickson et al. 2018) as well as non-economic issues (Boettcher et al. 2019).

The nature of lock in varies across the energy system. For example, lock-in in urban and transport sectors is different from the electricity sector. Broadly, urban environments involve infrastructural, institutional, and behavioural lock-in (Ürge-Vorsatz et al. 2018). Addressing lock-in in these sectors requires action by multiple stakeholders and is unlikely with just technological evolution (Table 6.11).

Committed carbon emissions are unevenly distributed. The disproportionate high share of committed emissions in emerging economies is the result of rapid growth in recent years, which has led to a comparably young fossil infrastructure with substantial remaining life (Shearer et al. 2017). Mature industrialized countries tend to have older infrastructures, part of which will be up for retirement in the near future (Tong et al. 2019). Coal-fired power plants currently planned or under construction are associated with 150-300 Gt-CO_2, of which ~75% and ~10% are located in Asia and the OECD respectively (Pfeiffer et al. 2018; Edenhofer et al. 2018). If implemented, these new fleets will further shorten all coal plants' lifetimes by another 10 years for meeting climate goals (Cui et al. 2019)

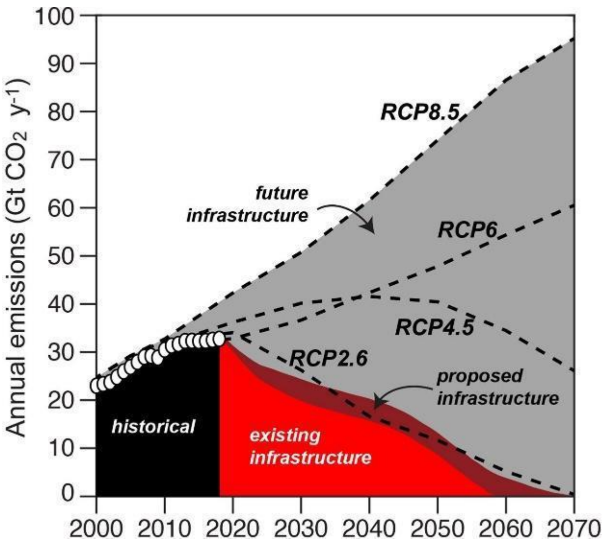


Figure 6.34 Annual emissions from existing, proposed, and future energy system infrastructure (Tong et al. 2019).

Despite the imperative to reduce use of fossil fuels and the multiple health and other benefits from closing coal-based infrastructure (Liu et al. 2019a; Portugal-Pereira et al. 2018; Rauner et al. 2020; Karlsson et al. 2020; Cui et al. 2021), coal power plants have continued to be commissioned globally (Jewell et al. 2019; Jakob et al. 2020), most notably in Asian countries. Gas power plants also continue to be built. In many regions, new fossil electricity generation exceeds needed capacity (Shearer et al. 2017).

Existing policies and the NDCs are insufficient to prevent an increase in fossil infrastructure and associated carbon lock in (*high confidence*) (Bertram et al. 2015; Johnson et al. 2015). Current investment decisions are critical because there is limited room within the carbon budget required to limit warming to well below 2°C (Rosenbloom 2019; Kalkuhl et al. 2019). Delays in mitigation will increase carbon lock-in and could result in large-scale stranded assets if stringency is subsequently increased to limit warming (Box 6.11). Near-term implementation of stringent GHG mitigation policies are likely to be most effective in reducing carbon lock-in (Haelg et al. 2018). Near-term mitigation policies will also need to consider different energy transition strategies as a result of different resources and carbon budgets between countries (Bos and Gupta 2018; Lucas 2016).

Near-term policy choices are particularly consequential for fast-growing economies. For example, Malik et al. (2020) found that 133 to 227 GW of coal capacity would be stranded after 2030 if India were to delay ambitious mitigation through 2030 and then pursue an ambitious, post-2030 climate strategy. (Cui et al. 2021)identified 18% of old, small, inefficient coal plants for rapid near-term retirement in China to help achieve air quality, health, water, and other societal goals and a feasible coal phaseout under climate goals. Comparable magnitudes of stranded assets may also be created in Latin America when adding all announced, authorized, and procured power plants up to 2060 (González-Mahecha et al. 2019). Options to reduce carbon lock in include reducing fossil fuels subsidies (Box 6.3), building CCS-ready facilities, or ensuring that facilities are appropriately designed for fuel switching (Budinis et al. 2018). Substantial lock-in may necessitate considerable deployment of CDR to compensate for high cumulative emissions.

Past and present energy sector investments have created technological, institutional, and behavioural path dependencies aligned towards coal, oil, and natural gas (*high confidence*). In several emerging economies, large projects are planned that address poverty reduction and economic development. Coal infrastructure may be the default choice for these investments without policies to invest in low-carbon infrastructure instead (Steckel et al. 2020; Joshua and Alola 2020). Path dependencies frequently have sustainability implications beyond carbon emissions. (Box 6.2 and Section 6.7.7). There are several SDG co-benefits associated with decarbonization of energy systems (Section 6.7.7; Sörgel et al. 2021). For example, coal mining communities frequently experience significant health and economic burdens from resource extraction.

[START BOX 6.13 HERE]

Box 6.13 Stranded Assets

Limiting likely warming to 2°C or below will result in stranded assets *(high confidence)*. Stranded assets can be broadly defined as assets which "suffer from unanticipated or premature write-offs, downward revaluations or [conversion] to liabilities." Stranded assets may create risks for financial market stability and macro-economic stability (Mercure et al. 2018, Battiston et al. 2017; Sen and von Schickfus 2020), and they will result in a rapid loss of wealth for the owners of affected assets (Vogt-Schilb and Hallegatte 2017; Ploeg and Rezai 2020).

There are two types of stranded assets: fossil-fuel resources that cannot be burned, and premature retirement of fossil infrastructure (e.g., power plants). About 30% of oil, 50% of gas, and 80% of coal reserves will remain unburnable if likely warming is limited to 2°C (Meinshausen et al. 2009; Leaton 2011; Leaton Ranger 2013; Pye et al. 2020; IRENA 2017b; Bauer et al. 2016; McGlade and Ekins 2015) (*high confidence*). Significantly more reserves are expected to remain unburned if warming is limited to 1.5°C. Countries with large oil, gas, and coal reserves are most at risk (Caldecott et al. 2017; Ansari and Holz 2020)

About 200 GW of fossil fuel electricity generation per year will likely need to be retired prematurely after 2030 to limit likely warming to 2°C, even if countries achieve their NDCs (Iyer et al. 2015; Johnson et al. 2015; Fofrich et al. 2020) (*medium confidence*). Limiting warming to 1.5°C will require significantly more rapid premature retirement of electricity generation capacity (Binsted et al. 2020). Coal- and gas-fired power plants will likely need to retire about 25 years earlier than in the past to limit likely warming to 2°C, and 30 years earlier to limit warming to 1.5°C (Cui et al. 2019; Fofrich et al. 2020). Coal-fired power plants are at significantly greater risk of stranding compared with gas-fired and oil-fired plants (Iyer et al. 2015; Johnson et al. 2015; Fofrich et al. 2020). The risks of stranded power plants are greatest in countries with newer fossil infrastructure.

If likely warming is limited to 2°C, the discounted economic impacts of stranded assets, including unburned fossil reserves, could be as high as USD 1-4 trillion from 2015 through 2050 (USD 10-20 trillion in undiscounted terms) (Mercure et al. 2018), IRENA, 2017) (*medium confidence*). About 40% of these impacts correspond to unburned fossil reserves (IRENA 2017b). If warming is limited to 1.5°C, the economic impacts of stranded assets are expected to be significantly higher (Binsted et al. 2020)

Stronger near-term mitigation will reduce premature retirements of fossil infrastructure, because more rapid mitigation will decrease new builds of fossil infrastructure that might later be stranded (Johnson et al. 2015; Bertram et al. 2018) (*high confidence*). For example, if likely warming is limited to 2°C, strengthening the NDC pledges beyond their 2015 levels could decrease stranded electricity sector assets by more than 50% (Iyer et al. 2015). By contrast, if countries fail to meet their NDCs and continue to build fossil infrastructure, mitigation will need to be accelerated beyond 2030, resulting up to double the amount of stranded electricity generation capacity (Iyer et al. 2015). This corresponds to a total undiscounted cost of about USD 2 trillion from electricity infrastructure alone, from the period 2015 to 2050 (IRENA 2017). CCS (6.4) could potentially help reduce hundreds of gigawatts stranded power plant capacity along with other fossil-based capital (Clark and Herzog 2014; Fan et al. 2018; Iyer et al. 2017).

[END BOX 6.13 HERE]

6.7.4 Fossil fuels in a low-carbon transition

Global fossil fuel use will need to decline substantially by 2050 to limit likely warming to 2°C or below, and it must decline substantially by 2030 to limit warming to 1.5°C with no or limited overshoot *(high confidence)*. Failing to reduce global fossil fuel use below today's levels by 2030 will make it more challenging to limit likely warming to below 2°C. *(high confidence)*. Fossil fuel use declines by 260-330 EJ (52-73% from 2020 levels, interquartile range) through 2050 to limit warming to 1.5°C with no or limited overshoot and 124-231 EJ (23-51% reduction compared to 2020 levels) to limit likely warming to 2°C; this will require a significant reduction in coal, oil and gas investments. Fossil fuels account for about 80% of primary energy today. In scenarios limiting warming to 1.5°C with limited or no overshoot, fossil energy provides 59-69% (interquartile range) primary energy in 2030 and 25-40s% primary energy in 2050 (AR6 database). In scenarios limiting likely warming to 2°C or below, fossil energy provides 71-75% (interquartile range) primary energy in 2030 and 41-57% primary energy in 2050 (AR6 database). The timeline for reducing production and usage varies across coal, oil, and gas due to their differing carbon intensities and their differing uses.

Global coal consumption without CCS needs to be largely eliminated by 2040-2050 to limit warming to 1.5°C, and 2050-2060 to limit likely warming to 2°C (*high confidence*). New investments in coal-fired electricity without CCS are inconsistent with limiting likely warming to 2°C or below (*high confidence*) (Spencer et al. 2018; Pfeiffer et al. 2018; Edenhofer et al. 2018; Cui et al. 2019). Coal consumption declines 130 EJ yr^{-1} to 140 EJ yr^{-1} in 2050 (79% to 99% compared to 2020 levels, interquartile range) in scenarios limiting warming to 1.5°C and 118 EJ yr^{-1} to 139 EJ yr^{-1} (66% to 98% compared to 2020 levels) in scenarios limiting likely warming to 2°C. Coal consumption without CCS falls by 67% to 82% (interquartile range) in 2030 in scenarios limiting warming to 1.5°C with no or limited overshoot. Studies indicate that coal use may decline substantially in the US and Europe over the coming decade based on the increasing competitiveness of low-carbon sources and near-term policy actions (Oei et al. 2020; Grubert and Brandt 2019). In several developing economies, the relative youth of the coal-fired electricity fleet will make a complete phaseout before 2050 difficult (Garg and Shukla 2009; Jewell et al. 2016). There are considerable differences in projected coal phaseout timelines in major Asian economies. Some studies suggest that coal may continue to be a part of the Chinese energy mix composing around a third of the total primary energy consumption by 2050 even if emissions are reduced by 50% by 2030 (He et al. 2020). Others indicate that a strategic transition would decrease the risk of stranded assets and enable a near-complete phaseout by 2050 (Wang et al. 2020a; Cui et al. 2021). This would entail prioritizing earlier retirements of plants based on technical (efficiency), economic (profitability, local employment) and environmental considerations (e.g., water scarcity for cooling).

Natural gas may remain part of energy systems through mid-century, both for electricity generation and use in industry and buildings, and particularly in developed economies, even if likely warming is limited to 2°C or less *(medium confidence)*. The decline in natural gas use in from 2020 to 2050 is 38 EJ yr^{-1} to 78 EJ yr^{-1} (21% to 61% decline from 2020 levels, interquartile range) in scenarios limiting warming to 1.5°C with no or limited overshoot and -22 EJ yr^{-1} to 46 EJ yr^{-1} (-13% to 36% decline from 2020 levels) in scenarios limiting likely warming to 2°C. Scenarios indicate that gas use in electricity will likely peak around 2035 and 2050 if warming is limited to 1.5°C with limited or no overshoot or likely below 2°C, respectively. There is variability in the role gas would play in future scenarios based on national climate commitments and availability of cheap renewable (Vrontisi et al. 2020, (Vishwanathan and Garg 2020; Malik et al. 2020). Note that these differences are not only present in the electricity sector but also in other end-uses.

While oil use is anticipated to decline substantially, due to changes in the transport sector, its use will likely continue through the mid-century, even if likely warming is limited to 2°C or less *(medium confidence)*. Oil use declines by 43 EJ yr^{-1} to 91 EJ yr^{-1} (19% to 54% from 2020 levels, interquartile range) in scenarios that limit warming to 1.5°C with no or limited overshoot and 46 EJ yr^{-1} to 109 EJ yr^{-1} (21% 60% from 2020 levels) by 2050 in scenarios that limit likely warming to 2°C. While oil use is anticipated to decline immediately in scenarios limiting warming to 1.5°C, it is likely to continue to be used through 2050. Oil use continues to be a significant source of transport fuels in most scenarios limiting likely warming to 2°C (Welsby et al, 2021). Oil use may reduce to about half of the current levels as a transport fuels (Feijoo et al. 2020) if likely warming is limited to 2°C, because of the availability of other options (biofuels, green hydrogen) and rapid deployment of EVs. In the absence of rapid transport electrification, the decline is slower with some studies projecting peak oil use around 2035 (Delgado et al. 2020; Pan et al. 2020).

There is a lack of consensus about how CCS might alter fossil fuel transitions for limiting likely warming to 2°C or below. CCS deployment will increase the shares of fossil fuels associated with limiting warming, and it can ease the economic transition to a low-carbon energy system (Muratori et al. 2016; Marcucci et al. 2019).While some studies find a significant role for fossil fuels with CCS by 2050 (Koelbl et al. 2014; Eom et al. 2015; Vishwanathan and Garg 2020), others find that retirement of unabated coal far outpaces the deployment of coal with CCS (McJeon et al, 2021; Budinis et al. 2018; Xie et al. 2020) Moreover, several models also project that with availability of CO_2 capture technology, BECCS might become significantly more appealing than fossil CCS even before 2050 (Luderer et al. 2018b; Muratori et al, 2017).

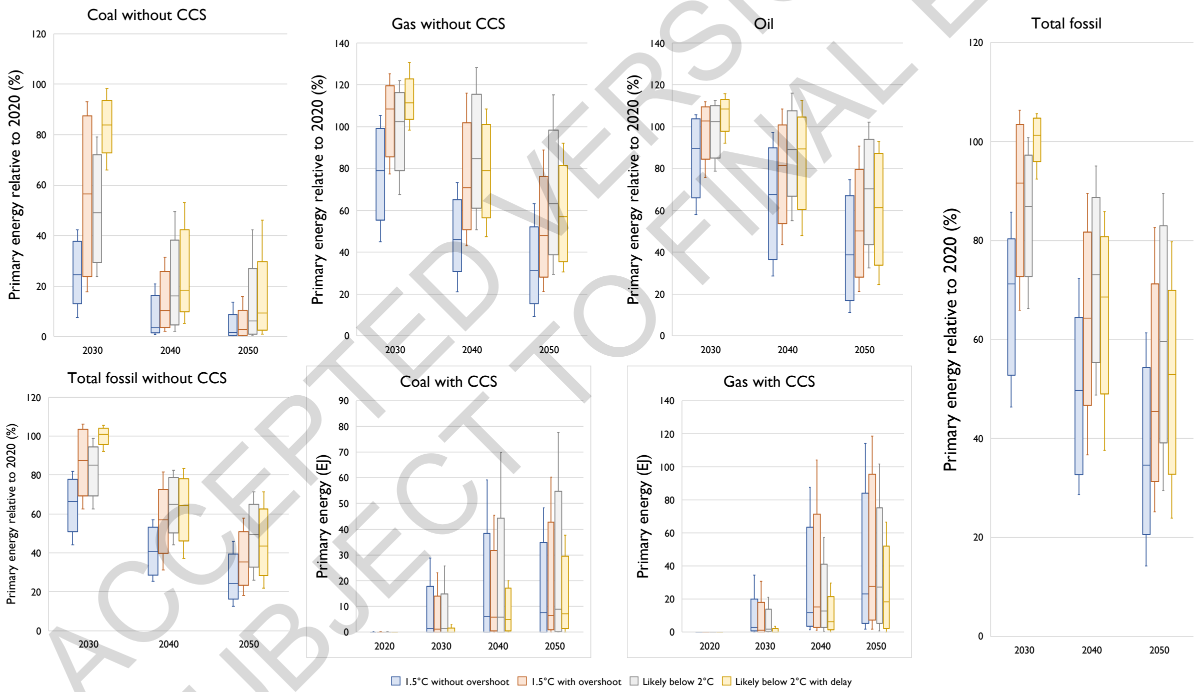


Figure 6.35 Global fossil fuel pathways for the 1.5°C scenarios (without and with overshoot), and likely 2°C scenarios (without and with delayed policy action) during 2020-2050 (Source: AR6 Scenario Database). Results for total consumption are expressed as a percentage relative to 2020 consumption. Results for fossil energy with CCS are expressed in total energy consumption. Boxes indicate 25th and 75th percentiles while whiskers indicate 5th and 95th percentiles. Oil use with CCS is not shown here as it remains below 5% of total use.

6.7.5 Policy and Governance

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

The literature discusses a broad set of policy approaches. Environmental economics focuses mainly on market-based approaches as the least-cost policy to achieve emission reductions (Kube et al. 2018). Many countries, however, have implemented policy mixes with a diverse set of complementary policies to achieve energy and climate policy targets. One example is the German Energiewende, which includes substantial support for renewables, an action plan for energy efficiency, and phase-out processes for nuclear- and coal-based power generation next to carbon pricing (Löschel et al. 2019). The halving of CO_2 emissions in UK power generation reflects multiple policies, particularly within the UK's Climate Change Act 2008 (Grubb and Newbery 2018). More generally, the implementation of the NDCs under the Paris Agreement are all characterized by diverse climate policy mixes.

These policy mixes (or policy packages) are shaped by different factors, including policy goals and objectives (including political, social and technological influences), multiple market, governance or behavioural failures or previous policy choices of earlier policy eras (Rogge 2017). When pursuing multiple policy goals or targeting some type of imperfection, well designed policy mixes can in principle reduce mitigation costs (Corradini et al. 2018) or address distributional concerns, especially vulnerable populations. For example, the interaction between carbon pricing and the support for clean energy technologies in the EU clean low-carbon strategy for 2050 can reduce mitigation costs and allow for the early adoption of more stringent climate targets (Vandyck et al. 2016). Policy efforts to promote adoption of low-carbon technologies are more successful if they focus not only on economic incentives but include behavioural interventions that target relevant cognitive and motivational factors (Khanna et al. 2021; Mundaca et al. 2019; see also Section 6.7.6). Overlapping nudges might not necessarily lead to lower effectiveness (Brandon et al. 2019).

Well-designed policy mixes can support the pursuit of multiple policy goals, target effectively different types of imperfections and framework conditions and take into account the technological, economical, and societal situation (*high confidence*). Accounting for the different development stages of new technologies will enhance low-emissions transitions (Graaf and Sovacool 2020). For prototype technologies and technologies in the demonstration phase, research subsidies and demonstration projects are most important. For technologies experiencing early adoption, infrastructure development and strengthening of markets are increasingly important, while retiring or repurposing of existing assets is important for mature technologies (IEA 2020h) Effective policy mixes will address different market frictions and deal with various uncertainties, for example, those pertaining to technological, climate, and socio-economic developments (Aldy 2020), but also with respect to outcomes of individual policies (e.g. Borenstein et al. 2019). Therefore, policy mixes may balance the trade-off between stability and the flexibility to change individual policies (Gawel and Lehmann 2019) and the policy mix over time (Rayner et al. 2017). Some policy instruments may become feasible over time, for example, as technological advancements reduce the transaction costs of comprehensive market-based approaches (Andoni et al. 2019; Di Silvestre et al. 2020), or as weakened barriers to stringency enable policy sequencing (Pahle et al. 2018) . Energy system policy mixes often include sector-specific regulation. Compared to economy-wide approaches, sectoral policies may be able to directly target specific sectors or mitigation options. However, uncoordinated implementation or limited coordination across sectors may lead to efficiency losses (e.g. Rosendahl et al. 2017). These losses also depend on other policies, such as pre-existing taxes (Goulder et al. 2016; Marten et al. 2018) or research and development policies (Acemoglu et al. 2016). Moreover, unilateral policies – those taken by individual countries in the absence of coordination with other countries – could raise carbon leakage risks, while balancing potential issues of (industrial) competitiveness (Martin et al. 2014; Rosendahl et al. 2017). Energy leakage may become more important during low-carbon energy systems. Numerous studies have identified pathways for carbon leakage in electricity markets with incomplete emission markets (Caron et al. 2015; Thurber et al. 2015; Murray and Maniloff 2015; Fell and Maniloff 2017; Duan et al. 2017; Qian et al. 2018). Well-designed policy mixes will need to target the whole life-cycle or value chains, for example, through policies on limiting fossil fuel extraction (Asheim et al. 2019), or they will need to include measures to limit carbon leakage (e.g. Cosbey et al. 2019).

Interactions between policy measures including their scope, stringency, and timing, influence the costs of reducing emissions (Corradini et al. 2018). In particular, some policy instruments may lead to lock-in effects (Section 6.7.3.), compete with other regulations (Graaf and Sovacool 2020), or trigger negative policy interactions (Perino 2015; Jarke-Neuert and Perino 2020). Existing policy mixes often reflect different political economy constraints and sometimes not well coordinated goals. The resulting policy mixes are often economically inefficient. However, comprehensive evaluation of policy mixes requires a broader set of criteria that reflect different considerations, such as broader goals (e.g., SDGs) and the feasibility of policies (*high confidence*).

Policy mixes might rather emerge piece-by-piece over time out of individual policy interventions rather than be designed as a whole from the outset (Howlett 2014; Rogge 2017) and may reflect differences across jurisdictions and sectors (Howlett 2014). For example, taking into account country-specific objectives, failures, and limitations, carbon prices may be only one part of a broader policy mix and thereby may not be uniform across countries (Bataille 2020). This lack of consistency makes it more difficult to assess economic outcomes since costs of complementary policies are often less visible and are often targeted at high-cost mitigation options (Borenstein et al. 2019).

Effective assessment of policy mixes requires comprehensive, validated international data, methodologies, and indicators. Existing policy mixes are difficult to evaluate because they target multiple objectives, and the evaluation must consider various criteria (Chapter 13, 6.7.7), such as environmental and economic effectiveness, distributional effects, transformative potential, institutional requirements, and feasibility. Economic outcomes depend on policy goals and implementation. Existing studies on policy mixes suggest the benefits of a comprehensive approach (Rosenow et al. 2017), while also highlighting that an “excessive” number of instruments may reduce overall effectiveness (Costantini et al. 2017). Combining environmental regulation and innovation policies may be of particular importance to tackle both emissions and innovation market failures (Fabrizi et al. 2018). The consistency and credibility of policy mixes is positively associated with green innovation (Rogge and Schleich 2018).

Potential future policies are difficult to evaluate due to methodological challenges (*high confidence*). Recent model-based analyses of future policy mixes based on “current policy scenarios” try to implement existing policies besides explicit or implicit carbon prices (den Elzen et al. 2016; Roelfsema et al. 2020; van Soest et al. 2017; Rogelj et al. 2016). Many assessments of future low-carbon energy transitions are still based on cost-optimal evaluation frameworks and include only limited analysis of interactions between policy measures. Hence they are often not describing real-world energy transitions properly, but rather differences in implied carbon prices, constraints in technology deployment, and timing of policies (Trutnevyte 2016).

6.7.6 Behaviour and Societal Integration

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

6.7.6.1 Strategies to encourage climate mitigation actions

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

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

Communicating financial consequences of behaviour seems less effective than emphasizing social rewards (Handgraaf et al. 2013) or benefits of actions for people (e.g., public health, comfort) and the environment (Asensio and Delmas 2015, 2016; Schwartz et al. 2015; Ossokina 2020; Bolderdijk et al. 2013). Financial appeals may have limited effects because they reduce people's focus on environmental consequences, weaken intrinsic motivation to engage in mitigation actions, provide a license to pollute (Agrawal et al. 2015; Bolderdijk and Steg 2015; Schwartz et al. 2015), and because pursuing small financial gains is perceived not worth the effort (Dogan et al. 2014; Bolderdijk et al. 2013).

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

Energy use feedback can promote energy saving behaviour within households (Grønhøj and Thøgersen 2011; Fischer 2008; Karlin et al. 2015; Delmas et al. 2013; Zangheri et al. 2019) and at work (Young et al. 2015), particularly when provided in real-time or immediately after the action so that people learn the impact of different actions (Faruqui et al. 2009; Delmas et al. 2013; Abrahamse et al. 2005; Tiefenbeck et al. 2016; Stern et al. 2016a; Yu et al. 2015). 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 savings as they immediately make sense and hardly require users' conscious attention. Feedback can make people aware of their previous mitigation behaviours, which can strengthen their environmental self-identity, and motivate them to engage in other mitigation actions as well as to act in line with their self-image (Van der Werff et al. 2014).

Social influence approaches that communicate what other people do or think can encourage mitigation actions (Clayton et al. 2015), as can social models of desired actions (Osbaldiston and Schott 2012; Abrahamse and Steg 2013; Wolske et al. 2020; Sussman and Gifford 2013). Feedback on one's own energy use relative to others can be effective (Nolan et al. 2008; Allcott 2011; Schultz et al. 2015), although not always, and effect sizes are small (Abrahamse and Steg 2013) compared to other types of feedback (Karlin et al. 2015).

Interventions that capitalize on people's motivation to be consistent can promote mitigation actions (Steg 2016). Examples are commitment strategies where people pledge to act (Abrahamse and Steg 2013; Lokhorst et al. 2013), implementation intentions where they additionally explicate how and when they will perform the relevant action and how they would cope with possible barriers (Rees et al. 2018; Bamberg 2000, 2002), and hypocrisy-related strategies that make people aware of inconsistencies between their attitudes and behaviour (Osbaldiston and Schott 2012).

Bottom-up approaches can promote mitigation action (Abrahamse and Steg 2013). Indeed, community energy initiatives can encourage members' low carbon behaviour (Middlemiss 2011; Seyfang and Haxeltine 2012; Abrahamse and Steg 2013; Sloot et al. 2018). Organizations can promote mitigation behaviour among their employees and customers by communicating their mission and strategies to mitigate climate change (van der Werff et al. 2021; Ruepert et al. 2017).

Default options, where a preset choice is implemented if users do not select another option, can promote mitigation actions such as energy savings, green electricity uptake, and meat-free meals options (Liebe et al. 2021; Pichert and Katsikopoulos 2008; Ölander and Thøgersen 2014; Kunreuther and Weber 2014; Bessette et al. 2014; Ebeling and Lotz 2015; Liebe et al. 2018; Campbell-Arvai et al. 2014).

6.7.6.2 Acceptability of policy, mitigation options and system changes

Public acceptability reflects the extent to which the public evaluates climate policy, mitigation options, and system changes (un)favourably, which can shape, enable, or prevent low-carbon energy system transitions. Public acceptability of policy and mitigation options is higher when people expect these have more positive and less negative consequences for self, others, and the environment (Demski et al. 2015; Drews and Van den Bergh 2016; Perlaviciute and Steg 2014). Public opposition may result when a culturally valued landscape is affected by renewable energy development (Warren et al. 2005; Devine-Wright and Howes 2010), particularly place-based identities are threatened (Devine-Wright 2009, 2013; Boudet 2019). Acceptability can increase after a policy or change has been implemented and the consequences appear to be more positive than expected (Carattini et al. 2018; Schuitema et al. 2010; Eliasson 2014; Weber 2015); effective policy trials can thus build public support.

Next, climate policy and low carbon options are evaluated as more fair and acceptable when costs and benefits are distributed equally, and when nature, the environment and future generations are protected (Schuitema et al. 2011; Drews and Van den Bergh 2016). Compensating affected groups for losses due to policy or systems changes enhanced public acceptability in some cases (Perlaviciute and Steg 2014), but people may disagree on which compensation would be worthwhile (Aitken 2010b; Cass et al. 2010), on the distribution of compensation (Devine-Wright and Sherry-Brennan 2019; Leer Jørgensen et al. 2020), or feel they are being bribed (Perlaviciute and Steg 2014; Cass et al. 2010). Pricing policies are more acceptable when revenues are earmarked for environmental purposes (Steg et al. 2006; Sælen and Kallbekken 2011) or redistributed towards those affected (Schuitema and Steg 2008).

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

Public support is higher when people trust responsible parties (Perlaviciute and Steg 2014; Jiang et al. 2018; Drews and Van den Bergh 2016; Michaels and Parag 2016; Liu et al. 2019a). Public support for unilateral climate policy is rather strong and robust (Bernauer et al. 2016a), even in the absence of reciprocal commitments by other states (Bernauer and Gampfer 2015).

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

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

The attractiveness of energy sector mitigation ultimately depends on the way that it provides benefits and reduces the costs for the many different priorities that societies value(Wei et al. 2018, 2020; Yang et al. 2018a). While costs and benefits of climate mitigation are often considered in the context of pure economic outcomes – for example, GDP effects or changes in value of consumption – costs and benefits should be viewed with a broader lens that accounts for the many ways that the energy system interacts with societal priorities (Karlsson et al. 2020). Climate mitigation is not separate from countries' broader growth and development strategies, but rather as a key element of those strategies.

Cost reductions in key technologies, particularly in electricity and light-duty transport, have increased the economic attractiveness of near-term low-carbon energy system transitions (*high confidence*). The near-term, economic outcomes of low-carbon energy system transitions in some sectors and regions may be on par with or superior to those of an emissions-intensive future (*high confidence*). Even in cases when system costs are higher for low-carbon transitions, these transitions may still be economically favourable when accounting for health impacts and other co-benefits (Gielen et al. 2019). Past assessments have quantified the aggregate economic costs for climate change mitigation using different metrics, for example carbon prices, GDP losses, investments in energy infrastructure, and energy system costs. Assessments of mitigation costs from integrated assessment and energy system models vary widely. For example, scenarios include carbon prices in 2030 of less than USD 20/t-CO_2, but also more than USD 400/t-CO_2 depending on the region, sector boundary, and methodology (e.g. (Bauer et al. 2016; Oshiro et al. 2017; Vaillancourt et al. 2017; Chen et al. 2019; Brouwer et al. 2016). Those arise both from different methodologies (Guivarch and Rogelj 2017) and assumptions about uncertainties in key factors that drive costs (Meyer et al. 2021)

Recent developments, however, raise the prospect that economic outcomes could be substantially superior to prior estimates, particularly if key technologies continue to improve rapidly. In some regions and circumstances, particularly in the electricity sector, near-term mitigation may well lead to superior economic outcomes than continuing to invest in and utilize emissions-intensive infrastructure (e.g. (Brown et al. 2017; Kumar et al. 2020). Given the importance of electricity decarbonization in near-term mitigation strategies (see Section 6.7.1), decreasing costs of solar PV, wind power, and batteries to support their integration, have an outsized influence on near-term economic outcomes from mitigation. At the same time, economic outcomes may vary across regions depending, among other things, on the characteristics of the current energy systems, energy resources, and needs for integrating VRE technologies.

The long-term economic characteristics of low-emissions energy system transitions are not well understood and depend on policy design and implementation along with future costs and availability of technologies in key sectors (e.g., process heat, long-distance transport), and the ease of electrification in end-use sectors (*high confidence*). The long-term aggregate economic outcomes from a low-emissions future are not likely to be substantially worse than in an emissions-intensive future and may prove superior (see, e.g., Bogdanov et al. 2021, Child et al. 2019, Farmer et al. 2020) (*medium confidence*). For the whole economy, the interquartile range of estimated mitigation costs is between USD_{2015} 140 and USD_{2015} 340/t-CO_2 in 2050 in scenarios limiting likely warming to 2°C and between USD_{2015} 430 and USD_{2015} 990/tCO_2 in scenarios limiting likely warming to 1.5°C (Chapter 3). For energy sectors in various regions and globally, different scenarios show a wide range of implied carbon prices in 2050 to limit warming to 1.5°C, from below USD 50/t-CO_2 to more than USD 900/t-CO_2 (Brouwer et al. 2016; Rogelj et al. 2018a). Mitigation costs for scenarios limiting likely warming to 2°C were 3-11% in consumption losses in AR5, but the median in newer studies is about 3% in GDP losses (Su et al. 2018; Gambhir et al. 2019).

Estimates of long run mitigation costs are highly uncertain and depend on various factors. Both faster technological developments and international cooperation are consistently found to improve economic outcomes (Paroussos et al. 2019). Long-term mitigation is likely to be more challenging than near-term mitigation because low-cost opportunities get utilized first and efforts after that would require mitigation in more challenging sectors (Section 6.6). Advances in low-carbon energy resources and carriers such as next-generation biofuels, hydrogen produced from electrolysis, synthetic fuels, and carbon-neutral ammonia would substantially improve the economics of net zero energy systems *(high confidence)*. Current estimates of cumulative mitigation costs are comparably high for developing countries, amounting to up to 2-3% of GDP, indicating difficulties for mitigation without adequate support from developed countries (Fujimori et al. 2020; Dorband et al. 2019). In scenarios involving large amounts of stranded assets, the overall costs of low-carbon transitions also include the additional costs of early retirements (Box 6.11).

Focusing only on aggregate economic outcomes neglects distributional impacts, impacts on broader SDGs, and other outcomes of broad societal importance. Strategies to increase energy efficiency and energy conservation are, in most instances, mutually reinforcing with strategies to support sustainable development. Improving efficiency and energy conservation will promote sustainable consumption and production of energy and associated materials (SDG-12) (*high confidence*). Contrastingly, successful implementation of demand-side options requires sustainable partnerships (SDG-17) between different actors in energy systems, for example governments, utilities, distributors, and consumers. Many authors have argued that energy efficiency has a large untapped potential in both supply and demand (Lovins 2018; Méjean et al. 2019). For example, improved fossil power plant efficiency has been estimated to lower the costs of CCS from USD 80-100/t-CO_2 for a subcritical plant to <USD 40/t-CO_2 for a high efficiency plant (Hu and Zhai 2017; Singh et al. 2017). This could enhance energy access and affordability. Eliminating electricity transmission losses has been estimated to mitigate 500 Mt-CO_2 per year globally (Surana and Jordaan 2019). For several other options, such as methane mitigation from the natural gas sector, the costs of infrastructure refurbishing could be offset with the value of the recovered natural gas (Kang et al. 2019).

Efficient end use technologies are likely to be particularly cost-effective in developing countries where new infrastructure is rapidly getting built and there is an opportunity to create positive path dependencies (Section 6.7.3). Aside from reducing energy consumption, efficient end use technologies reduce the need for resource extraction, for example, fossil fuel extraction or mining for materials used in wind turbines or solar PV cells (Luderer et al. 2019). Reduced resource extraction is an important precursor to SDG-12 on sustainable consumption and production of minerals. End use efficiency strategies also reduce the need for, and therefore SDG tradeoffs associated with, CDR towards the end of the century and avoid temperature overshoot (van Vuuren et al. 2018). But fully leveraging the demand-side efficiency would entail behavioural changes and thus rely on strong partnerships with communities (SDG-17). For instance, approaches that inform households of the economic value of conservation strategies at home could be particularly useful (Niamir et al. 2018). Improved energy efficiency is interlinked with higher economic growth in Africa (Ohene-Asare et al. 2020; Lin and Abudu 2020). An important distinction here between SDGs focusing on infrastructural and behavioural interventions is the temporal context. Improving building heat systems or the electricity grid with reduced T&D losses would provide climate mitigation with one-time investments and minor maintenance over decades. On the other hand, behavioural changes would be an ongoing process involving sustained, long-term societal interactions.

Increasing electrification will support and reduce the costs of key elements of human development, such as education, health, and employment) (*high confidence*). Greater access to electricity might offer greater access to irrigation opportunities for agricultural communities (Peters and Sievert 2016) which could have the potential increasing farmer incomes in support of SDG-1. Coordinated electrification policies also improve enrolment for all forms of education (Kumar and Rauniyar 2018; López-González et al. 2020). Empirical evidence from India suggests that electrification reduced the time for biomass collection thus improved the time children have available for schooling (SDG-4/5) (Khandker et al. 2014). Reduced kerosene use in developing countries has improved indoor air quality (SDG-3) (Barron and Torero 2017; Lewis and Severnini 2020). These positive linkages between climate change mitigation and other goals have improved perceptions of solar PV among the public and policymakers. "Goodwill" towards solar PV is the highest among all the major mitigation options considered in this chapter (Section 6.4.2).

Past trends have also indicated that in some Asian countries, electrification has been obtained at lower income levels as compared to developed countries (Rao and Pachauri 2017), with corresponding impacts for development goals For example, a human development index (HDI) greater than 0.7 (Figure 6.36) which signifies high development is now possible at close to 30 GJ yr^{-1} per person. This was attainable only at the energy consumption of 50 GJ yr^{-1} per person in preceding decades.

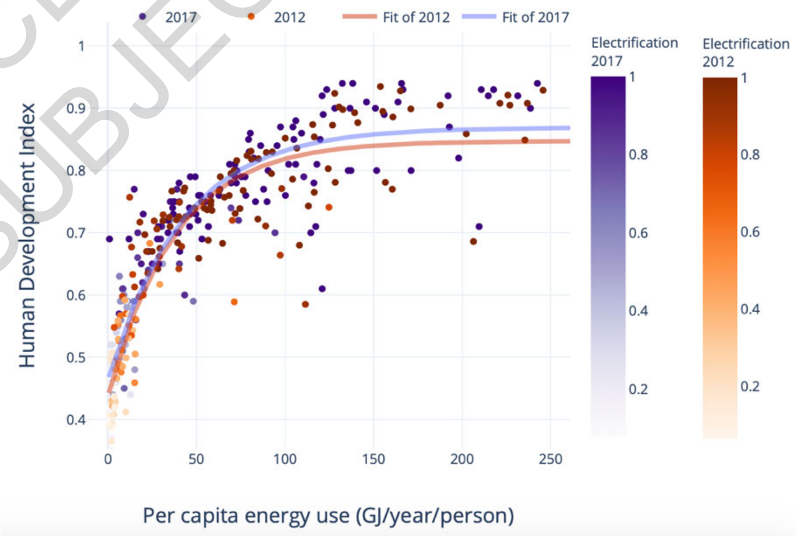


Figure 6.36 The relationship between total per capita energy use, rate of electrification and human development index. Improved efficiency has lowered the energy demand required for meeting a threshold HDI during 2012-2017

Electrification also improves energy efficiency, with corresponding implications for development goals For example, the availability of electric cooking may reduce the cooking primary energy requirement considerably compared to traditional stoves (Batchelor et al. 2019; Yang and Yang 2018; Khan and Alam 2020) while also promoting improved indoor air quality (SDG-3). Similarly, PV-powered irrigation and water pumping reduces pumping energy demands, which has the added advantage of promoting SDG-6 on clean water (Elkadeem et al. 2019; Rathore et al. 2018).

Phasing out fossil fuels in favour of low-carbon sources, is likely to have considerable SDG benefits, particularly if tradeoffs such as unemployment to fossil fuel workers are minimized (*high confidence*). A phaseout of coal (Box 6.2, Section 6.3) will support SDGs 3, 7 and 14, but it is also anticipated to create large job losses if not properly managed. At the same time, there are large potential employment opportunities that may be created in alternative sectors such as renewables and bioenergy for both skilled and unskilled workers. "Sustainable transition" pathways have indicated a complete fossil phaseout which could entail numerous other co-benefits. For instance, fossil fuels are estimated to generate only 2.65 jobs per USD 1M as compared to projected 7.49 from renewables (Garrett-Peltier 2017). Similar synergies may also emerge for nuclear power in the long-term though the high costs create tradeoffs in developing country contexts (Castor et al. 2020; Agyekum et al. 2020). While bioenergy production may create jobs, it may also be problematic for SDG-2 on zero hunger by affecting the supplies and prices of food. Phasing out of fossil fuels will also improve air quality (SDG-3) and premature deaths by reducing PM2.5 emissions, (He et al. 2020; Li et al. 2020c). Energy transitions from fossil fuels to renewables, as well as within fossil fuels (coal to gas switching), are already occurring in some regions, spurred by climate concerns, health concerns, market dynamics, or consumer choice (for example in the transport sector).

CDR and CCS can create significant land and water tradeoffs (*high confidence*). For large-scale CDR and CCS deployment to not conflict with development goals requires efforts to reduce implications on water and food systems. The water impacts of carbon capture are large, but these impacts can be strategically managed (Giannaris et al. 2020c; Magneschi et al. 2017; Realmonte et al. 2019; Liu et al. 2019a). In addition, high-salinity brines are produced from geologic carbon storage, which may be a synergy or tradeoff depending on the energy intensity of the treatment process and the reusability of the treated waters (Arena et al. 2017; Klapperich et al. 2014); if the produced brine from geologic formations can be treated via desalination technologies, there is an opportunity to keep the water intensity of electricity as constant (section 6.4.2.5). Both implications of CCS and CDR are related to SDG-6 on clean water. CDR discussions in the context of energy systems frequently pertains to BECCS which could affect food prices based on land management approaches (Daioglou et al. 2020a). Several CDR processes also require considerable infrastructure refurbishment and electrification to reduce upstream CO_2 emissions (Singh and Colosi 2021). Large-scale CDR could also open the potential for low-carbon transport and urban energy (by offsetting emissions in these sectors) use that would create synergies with SDG-11 (sustainable cities and communities). Effective siting of CDR infrastructure therefore requires consideration of tradeoffs with other priorities. At the same time, several SDG synergies have also been reported to accompany CCS projects such as with reduced air pollution (SDG-3) (Mikunda et al. 2021).

Greater energy system integration (Section 6.4.3, Section 6.6.2) would enhance energy-SDG synergies while eliminating tradeoffs associated with deploying mitigation options (*high confidence*). Energy system integration strategies focus on codependence of individual technologies in ways that optimize system performance. Accordingly, they can improve economic outcomes and reduce negative implications for SDG. For example, VRE electricity options raise intermittency concerns and hydrogen can be expensive due to the costs of electricity. Both are relevant to SDG-7 on affordable and reliable energy access. Routing excess solar generation during daytime for hydrogen production will improve grid stability as lower hydrogen costs (Tarroja et al. 2015). Due to the varying patterns of solar and wind energy, these two energy sources could be operated in tandem, thus reducing the material needs for their construction and for storage, thus promoting SDG-12 on sustainable production (Weitemeyer et al. 2015; Wang et al. 2019d). For CCS facilities, co-firing of fossil fuels and biomass could enable a more gradual, near-term low-carbon transition (Lu et al. 2019). This could enable early retirements (associated with SDG-1) while also providing air pollution reductions (associated with SDG-3).

Overall, the scope for positive interactions between low-carbon energy systems and SDGs is considerably larger than the tradeoffs (Figure 6.37) (McCollum et al. 2018b). Some critical tradeoffs include impact to biodiversity due to large-scale mineral mining needed for renewable infrastructure (Sonter et al. 2020).

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

Frequently Asked Questions

FAQ 6.1. Will energy systems that emit little or no CO_2 be different than those of today?

Low-carbon energy systems will be similar to those of today in that they will provide many of the same services as today – for example, heating and cooling homes, travelling to work or on vacation, transporting goods and services, and powering manufacturing. But future energy systems may be different in that people may also demand new services that aren't foreseen today, just as people now use energy for many information technology uses that were not anticipated 50 years ago. More importantly, low-carbon energy systems will be different in the way that energy is produced, transformed, and used to provide these services. In the future, almost all electricity will be produced from sources that emit little or no CO_2, such as solar power, wind power, nuclear power, bioenergy, hydropower, geothermal power, or fossil energy in which the CO_2 is captured and stored. Electricity, hydrogen, and bioenergy will be used in many situations where fossil fuels are used today, for example, in cars or heating homes. And energy is likely to be used more efficiently than today, for example, through more efficient cars, trucks, and appliances, buildings that use very little energy, and greater use or public transportation. All of these changes may require new policies, institutions, and even new ways for people to live their lives. And fundamental to all of these changes is that low-carbon energy systems will use far less fossil fuel than today.

FAQ 6.2. Can renewable sources provide all the energy needed for energy systems that emit little or no CO_2?

Renewable energy technologies harness energy from natural sources that are continually replenished, for example, from the sun (solar energy), the wind (wind energy), plants (bioenergy), rainfall (hydropower), or even the ocean. The energy from these sources exceeds the world's current and future energy needs many times. But that does not mean that renewable sources will provide all energy in future low-carbon energy systems. Some countries have a lot of renewable energy, whereas others do not, and other energy sources, such as nuclear power or fossil energy in which CO_2 emissions are captured and stored (carbon dioxide capture and storage, or CCS) can also contribute to low-carbon energy systems. The energy from sources such as solar energy, wind energy, and hydropower can vary throughout the day or over seasons or years. All low-carbon energy sources have other implications for people and countries, some of which are desirable, for example, reducing air pollution or making it easy to provide electricity in remote locations, and some of which are undesirable, for example decreasing biodiversity or mining of minerals to produce low-emissions technologies. For all of these reasons, it is unlikely that all low-carbon energy systems around the world will rely entirely on renewable energy sources.

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

To create a low-carbon energy system, emissions must be reduced across all parts of the system, and not just one or two. This means, for example, reducing the emissions from producing electricity, driving cars, hauling freight, heating and cooling buildings, powering data centers, and manufacturing goods. There are more opportunities to reduce emissions over the next decade in some sectors compared to others. For example, it's possible to substantially reduce electricity emissions over the next decade by investing in low-carbon electricity sources, while at the same time halting the construction of new coal-fired power plants, retiring existing coal-fired power plants or retrofitting them with CCS, and limiting the construction of new gas-fired power plants. There are also opportunities to increase the number of electric cars, trucks, and other vehicles on the road, or to use electricity rather than natural gas or coal to heat homes. And across the whole energy system, emissions can be reduced by using more efficient technologies. While these and other actions will be critical over the coming decade, it is also important to remember that the low-carbon energy transition needs to extend for many decades into the future to limit warming. This means that it is important now to improve and test out options that could be useful later on, for example, producing hydrogen from low-carbon sources or producing bioenergy from crops that require less land than those of today.

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Chapter 7: Agriculture, Forestry and Other Land Uses (AFOLU)

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Table of Contents

Executive summary

The Agriculture, Forestry and Other Land Uses[1] (AFOLU) sector encompasses managed ecosystems and offers significant mitigation opportunities while delivering food, wood and other renewable resources as well as biodiversity conservation, provided the sector adapts to climate change. Land-based mitigation measures represent some of the most important options currently available. They can both deliver carbon dioxide removal (CDR) and substitute for fossil fuels, thereby enabling emissions reductions in other sectors. The rapid deployment of AFOLU measures is essential in all pathways staying within the limits of the remaining budget for a 1.5◦C target *(high confidence)*. Where carefully and appropriately implemented, AFOLU mitigation measures are uniquely positioned to deliver substantial co-benefits and help address many of the wider challenges associated with land management. If AFOLU measures are deployed badly then, when taken together with the increasing need to produce sufficient food, feed, fuel and wood, they may exacerbate trade-offs with the conservation of habitats, adaptation, biodiversity and other services. At the same time the capacity of the land to support these functions may be threatened by climate change itself (*high confidence*). {WGI, Figure SPM7; WGII, 7.1, 7.6}

The AFOLU (managed land) sector, on average, accounted for 13-21% of global total anthropogenic greenhouse gas (GHG) emissions in the period 2010-2019 (*medium confidence*). At the same time managed and natural terrestrial ecosystems were a carbon sink, absorbing around one third of anthropogenic CO_2 emissions (*medium confidence*). Estimated anthropogenic net CO_2 emissions from AFOLU (based on bookkeeping models) result in a net source of +5.9 ± 4.1 $GtCO_2\ yr^{-1}$ between 2010 and 2019 with an unclear trend. Based on FAOSTAT or national GHG inventories, the net CO_2 emissions from AFOLU were 0.0 to +0.8 $GtCO_2\ yr^{-1}$ over the same period. There is a discrepancy in the reported CO_2 AFOLU emissions magnitude because alternative methodological approaches that incorporate different assumptions are used. If the managed and natural responses of all land to both anthropogenic environmental change and natural climate variability, estimated to be a gross sink of -12.5 ± 3.2 $GtCO_2\ yr^{-1}$ for the period 2010–2019, are included with land use emisisons, then land overall, constituted a net sink of -6.6 ± 5.2 $GtCO_2\ yr^{-1}$ in terms of CO_2 emissions (*medium confidence*). {WGI; 7.2, 7.2.2.5, Table 7.1}

AFOLU CO_2 emission fluxes are driven by land use change. The rate of deforestation, which accounts for 45% of total AFOLU emissions, has generally declined, while global tree cover and global forest growing stock levels are likely increasing (*medium confidence*). There are substantial regional differences, with losses of carbon generally observed in tropical regions and gains in temperate and boreal regions. Agricultural CH_4 and N_2O emissions are estimated to average 157 ± 47.1 $MtCH_4\ yr^{-1}$ and 6.6 ± 4.0 $MtN_2O\ yr^{-1}$ or 4.2 ± 1.3 and 1.8 ± 1.1 $GtCO_2$-eq yr^{-1} (using IPCC AR6 GWP_{100} values for CH_4 and N_2O) respectively between 2010 and 2019. AFOLU CH_4 emissions continue to increase (*high confidence*), the main source of which is enteric fermentation from ruminant animals (*high confidence*). Similarly, AFOLU N_2O emissions are increasing, dominated by agriculture, notably from manure application, nitrogen deposition, and nitrogen fertiliser use (*high confidence*). In addition to being a source and sink for GHG emissions, land plays an important role in climate through albedo effects, evapotranspiration and volatile organic compounds (VOCs) and their mix, although the

FOOTNOTE [1] For the AFOLU Sector, anthropogenic greenhouse gas emissions and removals by sinks are defined as all those occurring on 'managed land'. Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions.

combined role in total climate forcing is unclear and varies strongly with bioclimatic region and management type. {2.4.2.5, 7.2, 7.2.1, 7.2.3, 7.3}

The AFOLU sector offers significant near-term mitigation potential at relatively low cost but cannot compensate for delayed emission reductions in other sectors. (*high evidence, medium agreement*). The AFOLU sector can provide 20–30% (interquartile range) of the global mitigation needed for a 1.5 or 2ºC pathway towards 2050 (*robust evidence, medium agreement*), though there are highly variable mitigation strategies for how AFOLU potential can be deployed for achieving climate targets. The estimated *likely* economic (< USD100 tCO_2-eq^{-1}) AFOLU sector mitigation potential is 8 to 14 $GtCO_2$-eq yr^{-1} between 2020-2050, with the bottom end of this range representing the mean from integrated assessment models (IAMs) and the upper end representing the mean estimate from global sectoral studies. The economic potential is about half of the technical potential from AFOLU, and about 30-50% could be achieved under USD20 tCO_2-eq^{-1}. The implementation of robust measurement, reporting and verification processes is paramount to improving the transparency of net-carbon-stock-changes per land unit to prevent misleading assumptions or claims on mitigation. {7.1, 7.4, 7.5}

Between 2020 and 2050, mitigation measures in forests and other natural ecosystems provide the largest share of the economic (up to USD100 tCO_2-eq^{-1}) AFOLU mitigation potential, followed by agriculture and demand-side measures (*high confidence*). In the global sectoral studies, the protection, improved management, and restoration of forests, peatlands, coastal wetlands, savannas and grasslands have the potential to reduce emissions and/or sequester 7.3 mean (3.9–13.1 range) $GtCO_2$-eq yr^{-1}. Agriculture provides the second largest share of the mitigation potential, with 4.1 (1.7–6.7) $GtCO_2$-eq yr^{-1} (up to USD100 tCO_2-eq^{-1}) from cropland and grassland soil carbon management, agroforestry, use of biochar, improved rice cultivation, and livestock and nutrient management. Demand-side measures including shifting to sustainable healthy diets, reducing food waste, and building with wood and biochemicals and bio-textiles have a mitigation potential of 2.2 (1.1–3.6) $GtCO_2$-eq yr^{-1} . Most mitigation options are available and ready to deploy. Emissions reductions can be unlocked relatively quickly, whereas CDR needs upfront investment. Sustainable intensification in agriculture, shifting diets, and reducing food waste could enhance efficiencies and reduce agricultural land needs, and are therefore critical for enabling supply-side measures such as reforestation, restoration, as well as decreasing CH_4 and N_2O emissions from agricultural production. In addition, emerging technologies (e.g., vaccines or inhibitors) have the potential to substantially increase CH_4 mitigation potential beyond current estimates. AFOLU mitigation is not only relevant in countries with large land areas. Many smaller countries and regions, particularly with wetlands, have disproportionately high levels of AFOLU mitigation potential density. {7.4, 7.5}

The economic and political feasibility of implementing AFOLU mitigation measures is hampered by persistent barriers. Assisting countries to overcome barriers will help to achieve significant short-term mitigation (*medium confidence*). Finance forms a critical barrier to achieving these gains as currently mitigation efforts rely principally on government sources and funding mechanisms which do not provide sufficient resources to enable the economic potential to be realised. Differences in cultural values, governance, accountability and institutional capacity are also important barriers. Climate change could also emerge as a barrier to AFOLU mitigation, although the IPCC WGI contribution to AR6 indicated that an increase in the capacity of natural sinks may occur, despite changes in climate (*medium confidence*). The continued loss of biodiversity makes ecosystems less resilient to climate change extremes and this may further jeopardise the achievement of the AFOLU mitigation potentials indicated in this chapter (WGII and IPBES) (*high confidence*). {WGI Figure SPM7; 7.4, 7.6}

Bioenergy and other biobased options represent an important share of the total mitigation potential. The range of recent estimates for the technical bioenergy potential when constrained by food security and environmental considerations is 5–50 and 50–250 EJ yr^{-1} by 2050 for residues and dedicated biomass production system respectively. These estimates fall within previously estimated ranges (*medium agreement*). Poorly planned deployment of biomass production and afforestation options for in-forest carbon sequestration may conflict with environmental and social dimensions of sustainability (*high confidence).* The global technical CDR potential of BECCS by 2050 (considering only the technical capture of CO_2 and storage underground) is estimated at 5.9 mean (0.5-11.3) $GtCO_2$ yr^{-1}, of which 1.6 (0.8-3.5) $GtCO_2$ yr^{-1} is available at below USD100 tCO_2^{-1} (*medium confidence*). Bioenergy and other bio-based products provide additional mitigation through the substitution of fossil fuels fossil based products (*high confidence*). These substitution effects are reported in other sectors. Wood used in construction may reduce emissions associated with steel and concrete use. The agriculture and forestry sectors can devise management approaches that enable biomass production and use for energy in conjunction with the production of food and timber, thereby reducing the conversion pressure on natural ecosystems (*medium confidence*). {7.4}

The deployment of all land-based mitigation measures can provide multiple co-benefits, but there are also risks and trade-offs from misguided or inappropriate land management (*high confidence*). Such risks can best be managed if AFOLU mitigation is pursued in response to the needs and perspectives of multiple stakeholders to achieve outcomes that maximize synergies while limiting trade-offs (*medium confidence*). The results of implementing AFOLU measures are often variable and highly context specific. Depending on local conditions (e.g., ecosystem, climate, food system, land ownership) and management strategies (e.g., scale, method), mitigation measures have the potential to positively or negatively impact biodiversity, ecosystem functioning, air quality, water availability and quality, soil productivity, rights infringements, food security, and human wellbeing. Mitigation measures addressing GHGs may also affect other climate forcers such as albedo and evapotranspiration. Integrated responses that contribute to mitigation, adaptation, and other land challenges will have greater likelihood of being successful (*high confidence*); measures which provide additional benefits to biodiversity and human well-being are sometimes described as 'Nature-based Solutions'. {7.1, 7.4, 7.6}

AFOLU mitigation measures have been well understood for decades but deployment remains slow and emissions trends indicate unsatisfactory progress despite beneficial contributions to global emissions reduction from forest-related options (*high confidence*). Globally, the AFOLU sector has so far contributed modestly to net mitigation, as past policies have delivered about 0.65 $GtCO_2$ yr^{-1} of mitigation during 2010–2019 or 1.4% of global gross emissions (*high confidence*). The majority (>80%) of emission reduction resulted from forestry measures (*high confidence*). Although the mitigation potential of AFOLU measures is large from a biophysical and ecological perspective, its feasibility is hampered by lack of institutional support, uncertainty over long-term additionality and trade-offs, weak governance, fragmented land ownership, and uncertain permanence effects. Despite these impediments to change, AFOLU mitigation options are demonstrably effective and with appropriate support can enable rapid emission reductions in most countries. {7.4, 7.6}

Concerted, rapid and sustained effort by all stakeholders, from policy makers and investors to land owners and managers is a pre-requisite to achieving high levels of mitigation in the AFOLU sector (*high confidence*). To date USD0.7 billion yr^{-1} is estimated to have been spent on AFOLU mitigation. This is well short of the more than USD400 billion yr^{-1} that is estimated to be necessary to deliver the up to 30% of global mitigation effort envisaged in deep mitigation scenarios (*medium confidence)*. This estimate of the global funding requirement is smaller than current subsidies provided to agriculture and forestry. Making this funding available would require a change in flows of money and determination of who pays. A gradual redirection of existing agriculture and forestry subsidies would greatly advance mitigation. Effective policy interventions and national (investment) plans as part of Nationally Dertermined Contributions (NDCs), specific to local circumstances and needs, are urgently needed to accelerate the deployment of AFOLU mitigation options. These interventions are effective when they include funding schemes and long-term consistent support for implementation with governments taking the initiative together with private funders and non-state actors. {7.6}

Realizing the mitigation potential of the AFOLU sector depends strongly on policies that directly address emissions and drive the deployment of land-based mitigation options, consistent with carbon prices in deep mitigation scenarios (*high confidence*). Examples of successful policies and measures include establishing and respecting tenure rights and community forestry, improved agricultural management and sustainable intensification, biodiversity conservation, payments for ecosystem services, improved forest management and wood chain usage, bioenergy, voluntary supply chain management efforts, consumer behaviour campaigns, private funding and joint regulatory efforts to avoid e.g., leakage. The efficacy of different policies, however, will depend on numerous region-specific factors. In addition to funding, these factors include governance, institutions, long-term consistent execution of measures, and the specific policy setting (*high confidence*). {7.6}

There is a discrepancy, equating to 5.5 $GtCO_2$ yr^{-1} between alternative methods of accounting for anthropogenic land CO_2 fluxes. Reconciling these methods greatly enhances the credibility of AFOLU-based emissions offsetting. It would also assist in assessing collective progress in a global stocktake (*high confidence*). The principal accounting approaches are National GHG inventories (NGHGI) and global modelling approaches. NGHGI, based on IPCC guidelines, consider a much larger area of forest to be under human management than global models. NGHGI consider the fluxes due to human-induced environmental change on this area to be anthropogenic and are thus reported. Global models[2], in contrast, consider these fluxes to be natural and are excluded from the total reported anthropogenic land CO_2 flux. To enable a like-with-like comparison, the remaining cumulative global CO_2 emissions budget can be adjusted (*medium confidence*). In the absence of these adjustments, collective progress would appear better than it is. {Cross-Chapter Box 6 in this Chapter, 7.2}

Addressing the many knowledge gaps in the development and testing of AFOLU mitigation options can rapidly advance the likelihood of achieving sustained mitigation (*high confidence*). Research priorities include improved quantification of anthropogenic and natural GHG fluxes and emissions modelling, better understanding of the impacts of climate change on the mitigation potential, permanence and additionality of estimated mitigation actions, and improved (real time & cheap) measurement, reporting and verification. There is a need to include a greater suite of mitigation measures in IAMs, informed by more realistic assessments that take into account local circumstances and socio-economic factors and cross-sector synergies and trade-offs. Finally, there is a critical need for more targeted research to develop appropriate country-level, locally specific, policy and land management response options. These options could support more specific NDCs with AFOLU measures that enable mitigation while also contributing to biodiversity conservation, ecosystem functioning, livelihoods for millions of farmers and foresters, and many other Sustainable Development Goals (SDGs) (*high confidence*). {7.7}

FOOTNOTE [2] Book keeping models and dynamic global vegetation models

7.1 Introduction

7.1.1 Key findings from previous reports

Agriculture, Forestry and Other Land Uses (AFOLU) is unique due to its capacity to mitigate climate change through greenhouse gas (GHG) emission reductions, as well as enhance removals (IPCC 2019). However, despite the attention on AFOLU since early 1990s it was reported in the SRCCL as accounting for almost a quarter of anthropogenic emission (IPCC (2019a), with three main GHGs associated with AFOLU; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Overall emission levels had remained similar since the publication of AR4 (Nabuurs et al. 2007). The diverse nature of the sector, its linkage with wider societal, ecological and environmental aspects and the required coordination of related policy, was suggested to make implementation of known and available supply- and demand-side mitigation measures particularly challenging (IPCC 2019a). Despite such implementation barriers, the considerable mitigation potential of AFOLU as a sector on its own and its capacity to contribute to mitigation within other sectors was emphasised, with land-related measures, including bioenergy, estimated as capable of contributing between 20 and 60% of the total cumulative abatement to 2030 identified within transformation pathways (IPCC 2018). However, the vast mitigation potential from AFOLU initially portrayed in literature and in Integrated Assessment Models (IAMs), as explored in SR1.5, is being questioned in terms of feasibility (Roe et al. 2021) and a more balanced perspective on the role of land in mitigation is developing, while at the same time, interest by private investors in land-based mitigation is increasing fast.

The SRCCL (IPCC 2019a) outlined with *medium evidence* and *medium agreement* that supply-side agriculture and forestry measures had an economic (at USD100 tCO_2-eq^{-1}) mitigation potential of 7.2-10.6 $GtCO_2$-eq^{-1} in 2030 (using GWP_{100} and multiple IPCC values for CH_4 and N_2O) of which about a third was estimated as achievable at < USD20 tCO_2-eq^{-1}. Agricultural measures were reported as sensitive to carbon price, with cropland and grazing land soil organic carbon management having the greatest potential at USD20 tCO_2-eq^{-1} and restoration of organic soils at USD100 tCO_2-eq^{-1}. Forestry measures were less sensitive to carbon price, but varied regionally, with reduced deforestation, forest management and afforestation having the greatest potential depending on region. Although demand-side measures related to food could in theory make a large contribution to mitigation, in reality the contribution has been very small. Overall, the dependency of mitigation within AFOLU on a complex range of factors, from population growth, economic and technological developments, to the sustainability of mitigation measures and impacts of climate change, was suggested to make realisation highly challenging (IPCC 2019a).

Land can only be part of the solution alongside rapid emission reduction in other sectors (IPCC 2019a). It was recognised that land supports many ecosystem services on which human existence, wellbeing and livelihoods ultimately depend. Yet over-exploitation of land resources was reported as driving considerable and unprecedented rate of biodiversity loss, and wider environmental degradation (IPCC 2019a;IPBES 2019a). Urgent action to reverse this trend was deemed crucial in helping to accommodate the increasing demands on land and enhance climate change adaptation capacity. There was *high confidence* that global warming was already causing an increase in the frequency and intensity of extreme weather and climate events, impacting ecosystems, food security, disturbances and production processes, with existing (and new) carbon stocks in soils and biomass at serious risk. The impact of land cover on regional climate (through biophysical effects) was also highlighted, although there was *no confidence* regarding impacts on global climate.

Since AR5, the share of AFOLU to anthropogenic GHG emissions had remained largely unchanged at 13-21% of total GHG emissions (*medium confidence*), though uncertainty in estimates of both sources and sinks of CO_2, exacerbated by difficulties in separating natural and anthropogenic fluxes, was emphasised. Models indicated land (including the natural sink) to have *very likely* provided a net removal of CO_2 between 2007 and 2016. As in AR5, land cover change, notably deforestation, was identified as a major driver of anthropogenic CO_2 emissions whilst agriculture was a major driver of the increasing anthropogenic CH_4 and N_2O emissions.

In terms of mitigation, without reductions in overall anthropogenic emissions, increased reliance on large-scale land-based mitigation was predicted, which would add to the many already competing demands on land. However, some mitigation measures were suggested to not compete with other land uses, while also having multiple co-benefits, including adaptation capacity and potential synergies with some Sustainable Development Goals (SDGs). As in AR5, there was large uncertainty surrounding mitigation within AFOLU, in part because current carbon stocks and fluxes are unclear and subject to temporal variability. Additionally, the non-additive nature of individual measures that are often inter-linked and the highly context specific applicability of measures, causes further uncertainty. Many AFOLU measures were considered well-established and some achievable at low to moderate cost, yet contrasting economic drivers, insufficient policy, lack of incentivisation and institutional support to stimulate implementation among the many stakeholders involved, in regionally diverse contexts, was recognised as hampering realisation of potential.

None the less, the importance of mitigation within AFOLU was highlighted in all IPCC reports, with modelled scenarios demonstrating the considerable potential role and land-based mitigation forming an important component of pledged mitigation in Nationally Determined Contributions (NDCs) under the Paris Agreement. The sector was identified as the only one in which large-scale Carbon Dioxide Removal (CDR) may currently and at short term be possible (e.g. through afforestation/reforestation or soil organic carbon management). This CDR component was deemed crucial to limit climate change and its impacts, which would otherwise lead to enhanced release of carbon from land. However, the SRCCL emphasised that mitigation cannot be pursued in isolation. The need for integrated response options, that mitigate and adapt to climate change, but also deal with land degradation and desertification, while enhancing food and fibre security, biodiversity and contributing to other SDGs has been made clear (IPCC 2019a; Díaz et al. 2019; IPBES-IPCC 2021).

7.1.2 Boundaries, scope and changing context of the current report

This chapter assesses GHG fluxes between land and the atmosphere due to AFOLU, the associated drivers behind these fluxes, mitigation response options and related policy, at time scales of 2030 and 2050. Land and its management has important links with other sectors and therefore associated chapters within this report, notably concerning the provision of food, feed, fuel or fibre for human consumption and societal wellbeing (Chapter 5), for bioenergy (Chapter 6), the built environment (Chapter 9), transport (Chapter 10) and industry (Chapter 11). Mitigation within these sectors may in part, be dependent on contributions from land and the AFOLU sector, with interactions between all sectors discussed in Chapter 12. This chapter also has important links with IPCC WGII regarding climate change impacts and adaptation. Linkages are illustrated in Figure 7.1.

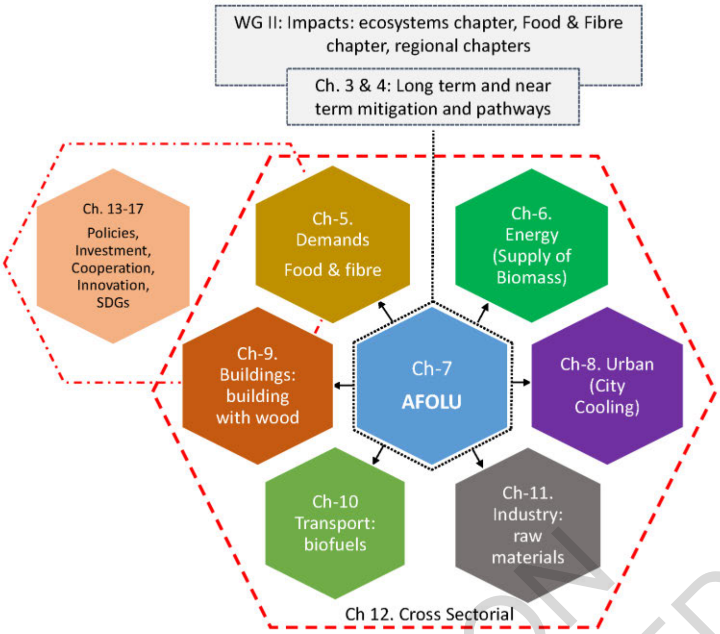

Figure 7.1 Linkage between Chapter 7 and other chapters within this report as well as to WGII. Mitigation potential estimates in this chapter consider potential emission reductions and removals only within the AFOLU sector itself, and not the substitution effects from biomass and biobased products in sectors such as Energy, Transport, Industry, Buildings, nor biophysical effects of e.g. cooling of cities. These are covered in their respective chapters.

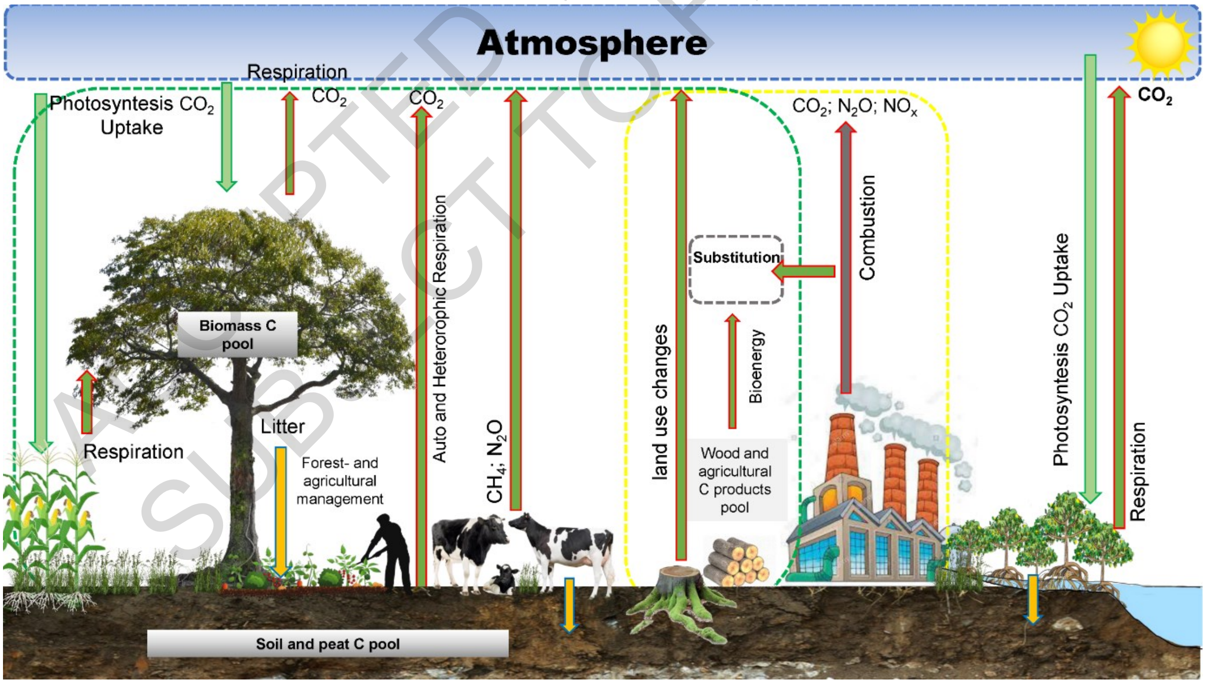

Figure 7.2 Summarised representation of interactions between land management, its products in terms of food and fibre, and land - atmospheric GHG fluxes. For legibility reasons only a few of the processes and management measures are depicted.

As highlighted in both AR5 and the SRCCL, there is a complex interplay between land management and GHG fluxes as illustrated in Figure 7.2, with considerable variation in management regionally, as a result of geophysical, climatic, ecological, economic, technological, institutional and socio-cultural diversity. The capacity for land-based mitigation varies accordingly. The principal focus of this chapter is therefore, on evaluating regional land-based mitigation potential, identifying applicable AFOLU mitigation measures, estimating associated costs and exploring policy options that could enable implementation.

Mitigation measures are broadly categorised as those relating to (1) forests and other ecosystems (2) agriculture (3) biomass production for products and bioenergy and (4) demand-side levers. Assessment is made in the context that land-mitigation is expected to contribute roughly 25% of the 2030 mitigation pledged in Nationally Determined Contributions (NDCs) under the Paris Agreement (Grassi et al. 2017), yet very few countries have provided details on how this will be achieved. In light of AR5 and the SRCCL findings, that indicate large land-based mitigation potential, considerable challenges to its realisation, but also a clear nexus at which humankind finds itself, whereby current land management, driven by population growth and consumption patterns, is undermining the very capacity of land, a finite resource, to support wider critical functions and services on which humankind depends. Mitigation within AFOLU is occasionally and wrongly perceived as an opportunity for in-action within other sectors. AFOLU simply cannot compensate for mitigation shortfalls in other sectors. As the outcomes of many critical challenges (UN Environment 2019), including biodiversity loss (Díaz et al. 2019) and soil degradation (FAO and ITPS 2015), are inextricably linked with how we manage land, the evaluation and assessment of AFOLU is crucial. This chapter aims to address three core topics;

1. What is the latest estimated (economic) mitigation potential of AFOLU measures according to both sectoral studies and integrated assessment models, and how much of this may be realistic within each global region?
2. How do we realise the mitigation potential, while minimising trade-offs and risks and maximising co-benefits that can enhance food and fibre security, conserve biodiversity and address other land challenges?
3. How effective have policies been so far and what additional policies or incentives might enable realisation of mitigation potential and at what costs?

This chapter first outlines the latest trends in AFOLU fluxes and the methodology supporting their estimation (Section 7.2). Direct and indirect drivers behind emission trends are discussed in Section 7.3. Mitigation measures, their costs, co-benefits, trade-offs, estimated regional potential and contribution within integrated global mitigation scenarios, is presented in Sections 7.4 and 7.5 respectively. Assessment of associated policy responses and links with SDGs are explored in Section 7.6. The chapter concludes with gaps in knowledge (Section 7.7) and frequently asked questions.

7.2 Historical and current trends in GHG emission and removals; their uncertainties and implications for assessing collective climate progress

The biosphere on land and in wetlands is a source and sink of CO_2 and CH_4, and a source of N_2O due to both natural and anthropogenic processes that happen simultaneously and are therefore difficult to disentangle (IPCC 2010; Angelo and Du Plesis 2017; IPCC 2019a). AFOLU is the only GHG sector to currently include anthropogenic sinks. A range of methodological approaches and data have been applied to estimating AFOLU emissions and removals, each developed for their own purposes, with estimates varying accordingly. Since the SRCCL (Jia et al. 2019), emissions estimates have been updated (Sections 7.2.2 and 7.2.3), while the assessment of biophysical processes and short-lived climate forcers (Section 7.2.4) is largely unchanged. Further progress has been made on the implications of differences in AFOLU emissions estimates for assessing collective climate progress (Section 7.2.2.2, Cross-Chapter Box 6 in this Chapter).

7.2.1 Total net GHG flux from AFOLU

National Greenhouse Gas Inventory (NGHGI) reporting following the IPCC 1996 guidelines (IPCC 1996), separates the total anthropogenic AFOLU flux into: (i) net anthropogenic flux from Land Use, Land-Use Change, and Forestry (LULUCF) due to both change in land cover and land management; and (ii) the net flux from Agriculture. While fluxes of CO_2 (Section 7.2.2) are predominantly from LULUCF and fluxes of CH_4 and N_2O (Section 7.2.3) are predominantly from agriculture, fluxes of all three gases are associated with both sub-sectors. However, not all methods separate them consistently according to these sub-sectors, thus here we use the term AFOLU, separate by gas and implicitly include CO_2 emissions that stem from the agriculture part of AFOLU, though these account for a relatively small portion.

Table 7.1 Net anthropogenic emissions (annual averages for 2010–2019[a]) from Agriculture, Forestry and Other Land Use (AFOLU). For context, the net flux due to the natural response of land to climate and environmental change is also shown for CO_2 in column E. Positive values represent emissions, negative values represent removals.

Anthropogenic						Natural Response	Natural + Anthropogenic
Gas	**Units**	**AFOLU Net anthropogenic emissions [h]**	**Non-AFOLU anthropogenic GHG emissions [d, f]**	**Total net anthropogenic emissions (AFOLU + non-AFOLU) by gas**	**AFOLU as a % of total net anthropogenic emissions by gas**	**Natural land sinks including natural response of land to anthropogenic environmental change and climate variability [e]**	**Net-land atmosphere CO_2 flux (i.e. anthropogenic AFOLU + natural fluxes across entire land surface**
		A	**B**	**C = A+B**	**D = (A/C) *100**	**E**	**F=A+E**
CO_2	$GtCO_2$-eq yr^{-1}	5.9 ± 4.1 [b, f] (bookkeeping models only). 0 to 0.8 (NGHGI/ FAOSTAT data)	36.2 ± 2.9	42.0 ± 29.0	14%	**-12.5 ± 3.2**	**-6.6 ± 4.6**
CH_4	$MtCH_4$ yr^{-1}	157.0 ± 47.1 [c]	207.5 ± 62.2	364.4 ± 109.3		- [i]	
	$GtCO_2$-eq yr^{-1}	4.2 ± 1.3 [g]	5.9 ± 1.8	10.2 ± 3.0	41%		
N_2O	MtN_2O yr^{-1}	6.6 ± 4.0 [c]	2.8 ± 1.7	9.4 ± 5.6			
	$GtCO_2$-eq yr^{-1}	1.8 ± 1.1 [g]	0.8 ± 0.5	2.6 ± 1.5	69%		
Total [j]	$GtCO_2$-eq yr^{-1}	11.9 ± 4.4 (CO_2 component considers bookkeeping models only)	44 ± 3.4	55.9 ± 6.1	21%		

[a] Estimates are given until 2019 as this is the latest date when data are available for all gases, consistent with Chapter 2, this report. Positive fluxes are emission from land to the atmosphere. Negative fluxes are removals.

[b] Net anthropogenic flux of CO_2 are due to land-use change such as deforestation and afforestation and land management, including wood harvest and regrowth, peatland drainage and fires, cropland and grassland management. Average of three bookkeeping models (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020), complemented by data on peatland drainage and fires from FAOSTAT (Prosperi et al. 2020) and

GFED4s (Van Der Werf et al. 2017). This number is used for consistency with WGI and Chapter 2, this report. Comparisons with other estimates are discussed in 7.2.2. Based on NGHGIs and FAOSTAT, the range is 0 to 0.8 Gt CO_2 yr^{-1}.

[c] CH_4 and N_2O emission estimates and assessed uncertainty of 30 and 60% respectively, are based on EDGAR data (Crippa et al. 2021) in accordance with Chapter 2, this report (Sections 2.2.1.3 and 2.2.1.4). Both FAOSTAT (FAO 2021a; Tubiello 2019; USEPA 2019) and the USA EPA (USEPA 2019) also provide data on agricultural non-CO_2 emissions, however mean global CH_4 and N_2O values considering the three databases are within the uncertainty bounds of EDGAR. EDGAR only considers agricultural and not overall AFOLU non-CO_2 emissions. Agriculture is estimated to account for approximately 89 and 96% of total AFOLU CH_4 and N_2O emissions respectively. See Section 7.2.3 for further discussion.

[d] Total non-AFOLU emissions are the sum of total CO_2-eq emissions values for energy, industrial sources, waste and other emissions with data from the Global Carbon Project for CO_2, including international aviation and shipping, and from the PRIMAP database for CH_4 and N_2O averaged over 2007-2014, as that was the period for which data were available.

[e] The modelled CO_2 estimates include natural processes in vegetation and soils and how they respond to both natural climate variability and to human-induced environmental changes i.e. the response of vegetation and soils to environmental changes such as increasing atmospheric CO_2 concentration, nitrogen deposition, and climate change (indirect anthropogenic effects) on both managed and unmanaged lands. The estimate shown represents the average from 17 Dynamic Global Vegetation Models with 1SD uncertainty (Friedlingstein et al. 2020)

[f] The NGHGIs take a different approach to calculating "anthropogenic" CO_2 fluxes than the models (Section 7.2.2). In particular the sinks due to environmental change (indirect anthropogenic fluxes) on managed lands are generally treated as anthropogenic in NGHGIs and non-anthropogenic in models such as bookkeeping and IAMs. A reconciliation of the results between IAMs and NGHGIs is presented in Cross-Chapter Box 6 in this Chapter. If applied to this table, it would transfer approximately -5.5 $GtCO^2$ y^{-1}(a sink) from Column E (which would become --7.2 $GtCO_2$ yr^{-1}) to Column A (which would then be 0.4 $GtCO_2$ yr^{-1}).

[g] All values expressed in units of CO_2-eq are based on IPCC AR6 100-year Global Warming Potential (GWP_{100}) values with climate-carbon feedbacks (CH_4 = 27, N_2O = 273) (Chapter 2, Supplementary Material SM2.3 and IPCC WGI AR6 Section 7.6).

[h] For assessment of cross-sector fluxes related to the food sector, see Chapter 12, this report.

[i] While it is acknowledged that soils are a natural CH_4 sink (Jackson et al. 2020) with soil microbial removals estimated to be 30 ± 19 $MtCH_4$ yr^{-1} for the period 2008-2017 (according to bottom-up estimates), natural CH_4 sources are considerably greater (371 (245-488) $MtCH_4$ yr^{-1}) resulting in natural processes being a net CH_4 source (IPCC WGI AR6 Section 5.2.2). The soil CH_4 sink is therefore omitted from Column E.

[j] Total GHG emissions concerning non-AFOLU sectors and all sectors combined (Columns B and C) include fluorinated gases in addition to CO_2, CH_4 and N_2O. Therefore, total values do not equal the sum of estimates for CO_2, CH_4 and N_2O.

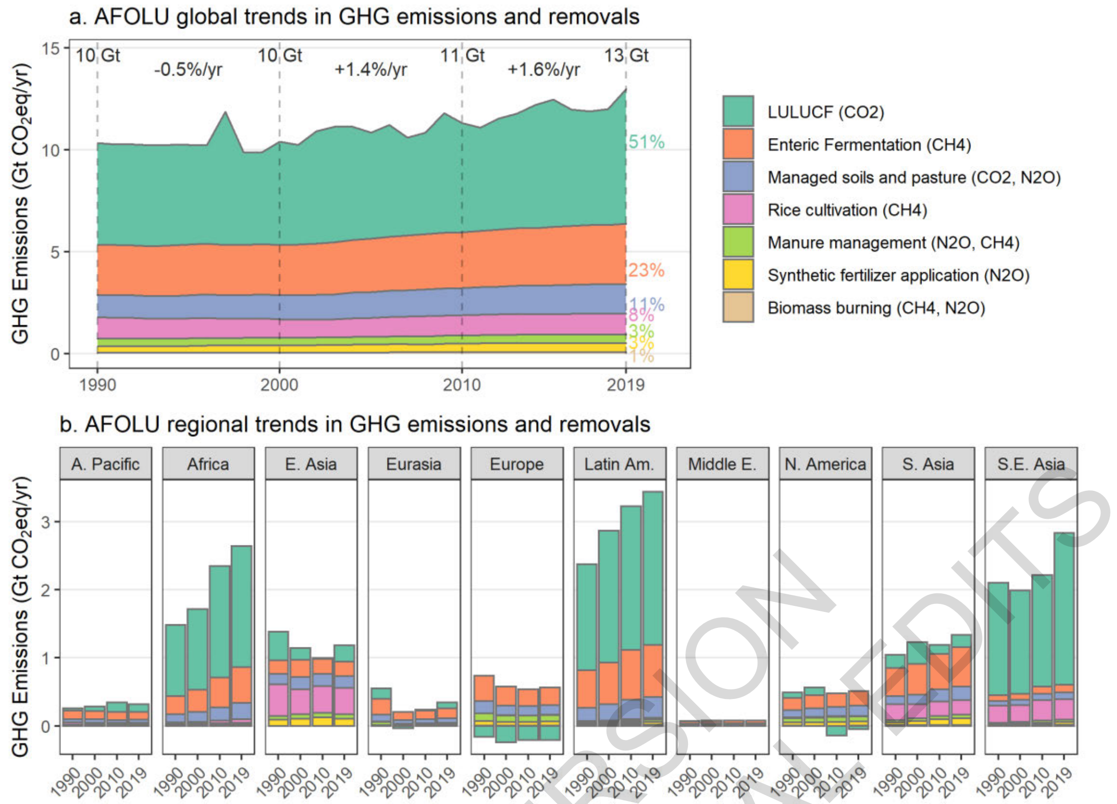

Figure 7.3 Subdivision of the total AFOLU emissions from Table 7.1 by activity and gas for the period 1990 to 2019. Positive values are emissions from land to atmosphere, negative values are removals. Panel A shows emissions divided into major activity and gases. Note that 'biomass burning' is only the burning of agriculture residues in the fields. The indicated growth rates between 1990-2000, 2000-2010, 2010-2019 are annualised across each time period. Panel B illustrates regional emissions in the years 1990, 2000, 2010, 2019 AFOLU CO_2 (green shading) represents all AFOLU CO_2 emissions. It is the mean from three bookkeeping models (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020) as presented in the Global Carbon Budget (Friedlingstein et al. 2020) and is <u>not directly comparable to LULUCF in NGHGIs (Section 7.2.2).</u> Data onCH_4 and N_2O emissions are from the EDGAR database (Crippa et al. 2021). See Sections 7.2.2 and 7.2.3 for comparison of different datasets. All values expressed are asCO_2-eq with GWP_{100} values: CH_4 = 27, N_2O = 273.

Total global net anthropogenic GHG emissions from AFOLU were 11.9 ± 4.4 GtCO2-eq yr^{-1} on average over the period 2010-2019, around 21% of total global net anthropogenic GHG emissions (Table 7.1, Figure 7.3, using the sum of bookkeeping models for the CO_2 component). When using FAOSTAT/NGHGIs CO_2 flux data, then the contribution of AFOLU to total emissions amounts to 13% of global emissions.

This AFOLU flux is the net of anthropogenic emissions of CO_2, CH_4 and N_2O, and anthropogenic removals of CO_2. The contribution of AFOLU to total emissions varies regionally with highest in Latin America and Caribbean with 58% an lowest in Europe and North America with each 7% (Chapter 2, Section 2.2.3). There is a discrepancy in the reported CO_2 AFOLU emissions magnitude because alternative methodlogical approaches that incorporate different assumptions are used (see 7.2.2.2). While there is *low agreement* in the trend of global AFOLU CO_2 emissions over the past few decades (7.2.2), they have remained relatively constant (*medium confidence*) (Chapter 2). Average non-CO_2 emission (aggregated using GWP_{100} IPCC AR6 values) from agriculture have risen from 5.2 ± 1.4 $GtCO_2$-eq yr^{-1} for the period 1990 to 1999, to 6.0 ± 1.7 $GtCO_2$-eq yr^{-1} for the period 2010 to 2019 (Crippa et al. 2021), Section 7.2.3).

To present a fuller understanding of land-atmosphere interactions, Table 7.1 includes an estimate of the natural sink of land to atmospheric CO_2 (IPCC WGI Chapter 5 and (Jia et al. 2019). Land fluxes respond naturally to human-induced environmental change (e.g. climate change, and the fertilising effects of increased atmospheric CO_2 concentration and nitrogen deposition), known as "indirect anthropogenic effects", and also to "natural effects" such as climate variability (IPCC 2010) (Table 7.1, Section 7.2.2). This showed a removal of -12.5 ± 3.2 $GtCO_2$ yr^{-1} (*medium confidence*) from the atmosphere during 2010-2019 according to global DGVM models (Friedlingstein et al. 2020) 31% of total anthropogenic net emissions of CO_2 from all sectors. It is likely that the NGHIs and FAOSTAT implicitly cover some part of this sink and thus provide a net CO_2 AFOLU balance with some 5 $GtCO_2$ lower net emissions than according to bookkeeping models, with the overall net CO_2 value close to being neutral. Model results and atmospheric observations concur that, when combining both anthropogenic (AFOLU) and natural processes on the entire land surface (the total "land-atmosphere flux"), the land was a global net sink for CO_2 of -6.6 $\pm$ 4.6 $GtCO_2$ yr^{-1} with a range for 2010 to 2019 from -4.4 to -8.4 $GtCO_2$ yr^{-1}. (Van Der Laan-Luijkx et al. 2017; Rödenbeck et al. 2003, 2018; Chevallier et al. 2005; Feng et al. 2016; Niwa et al. 2017; Patra et al. 2018). The natural land sink is *highly likely* to be affected by both future AFOLU activity and climate change (IPCC WGI Box 5.1 and IPCC WGI SPM Figure 7), whereby under more severe climate change, the amount of carbon stored on land would still increase although the relative share of the emissions that land takes up, declines.

7.2.2 Flux of CO_2 from AFOLU, and the non-anthropogenic land sink

7.2.2.1 Global net AFOLU CO_2 flux

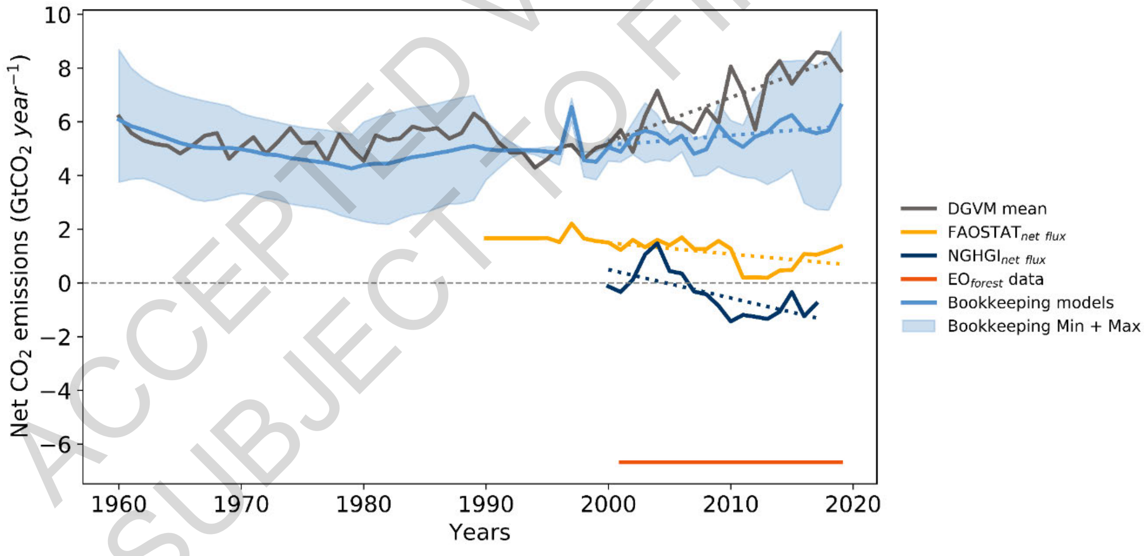

Figure 7.4 Global net CO_2 flux due to AFOLU estimated using different methods for the period 1960 to 2019 ($GtCO_2$ yr^{-1}). Positive numbers represent emissions. (Grey line) The mean from 17 DGVMs all using the same driving data under TrendyV9 used within the Global Carbon Budget 2020 and including different degrees of management (Bastos et al. 2020; Friedlingstein et al. 2020). (Orange line) Data downloaded 6th June 2021 from FAOSTAT (FAO 2021b; http://www.fao.org/faostat/) comprising: net emissions from (i) forest land converted to other land, (ii) net emissions from organic soils in cropland, grassland and from biomass burning (including peat fires and peat draining (Prosperi et al. 2020) and (iii) net emissions from forest land remaining forest land, which includes managed forest lands (Tubiello et al. 2020). (Dark blue line) Net flux estimate from National Greenhouse Gas Inventories (NGHGI) based on

country reports to the UNFCCC for LULUCF (Grassi et al. 2021) which include land-use change, and flux in managed lands. (Red (EO) line) The 2001 – 2019 average net CO_2 flux from non-intact forest-related emissions and removals based on ground and Earth Observation data (EO) (Harris et al. 2021). Data to mask non-intact forest were used in the tropics (Turubanova et al. 2018) and extra-tropics (Potapov et al. 2017).

Light blue line: the mean estimate and minimum and maximum (blue shading) from three bookkeeping models (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020). These include land cover change (e.g. deforestation, afforestation), forest management including wood harvest and land degradation, shifting cultivation, regrowth of forests following wood harvest or abandonment of agriculture, grassland management, agricultural management. Emissions from peat burning and draining are added from external data sets (see text). Both the DGVM and Bookkeeping global data is available at: https://www.icos-cp.eu/science-and-impact/global-carbon-budget/2020 (Accessed on 04/010/2021). Data consistent with IPCC WGI Chapter 5. Dotted lines denote the linear regression from 2000 to 2019. Trends are statistically significant ($P < 0.05$) with exception for the NGHGI trend ($P < 0.01$).

Comparison of estimates of the global net AFOLU flux of CO_2 from diverse approaches (Figure 7.4) show differences on the order of several $GtCO_2$ yr^{-1}. When considering the reasons for the differences, and an approach to reconcile them (Section 7.2.2.3; Grassi et al. 2021), there is *medium confidence* in the magnitude of the net AFOLU CO_2 flux. There is a discrepancy in the reported CO_2 AFOLU emissions magnitude because alternative methodological approaches that incorporate different assumptions are used (see 7.2.2.2). While the mean of the bookkeeping and DGVM model's show a small increase in global CO_2 net emissions since year 2000, individual models suggest opposite trends (Friedlingstein et al. 2020). The latest FAOSTAT and NGHGI estimates show a small reduction in net emission. Overall, the trends are unclear.

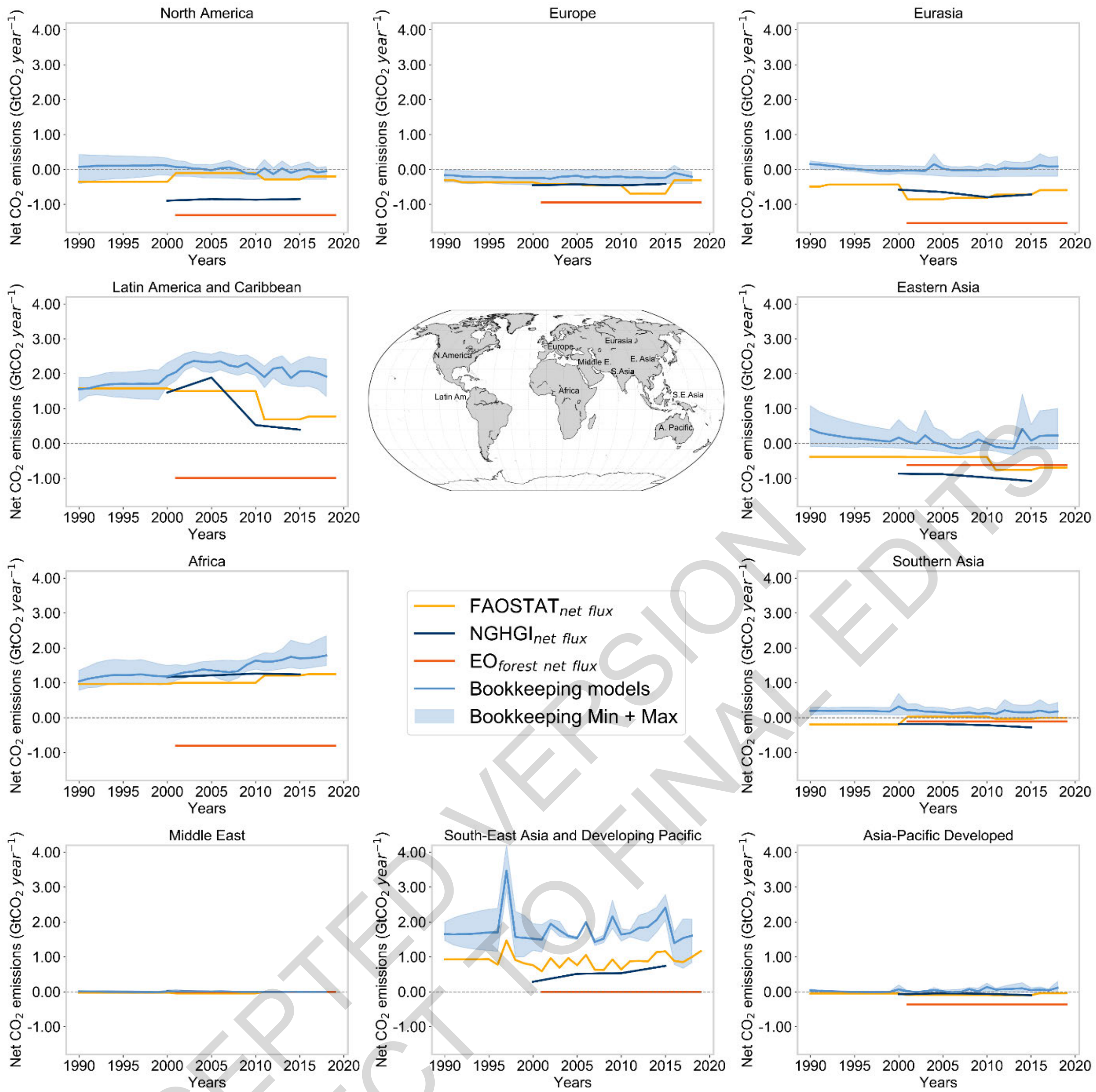

Figure 7.5 Regional net flux of CO_2 due to AFOLU estimated using different methods for the period 1990-2019 ($GtCO_2$ yr^{-1}). Positive numbers represent emissions. The upper-central panel depicts the world map shaded according to the IPCC AR6 regions corresponding to the individual graphs. For each regional panel; (Orange line) Total net flux data from FAOSTAT (Tubiello et al. 2020), (Dark blue line) Net emissions estimates from National Greenhouse Gas Inventories based on country reports to the UNFCCC for LULUCF (Grassi et al. 2021), (Light blue line) The mean estimate and minimum and maximum (blue shading) from three bookkeeping models. (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020). Regional estimates from bookkeeping models are available at: https://zenodo.org/record/5548333#.YVwJB2LMJPY (Minx et al. 2021). See the legend in Figure 7.4 for a detailed explanation of flux components for each dataset.

Regionally (Figure 7.5), there is *high confidence* of net emissions linked to deforestation in Latin America, Africa and South-East Asia from 1990 to 2019. There is *medium confidence* in trends indicating a decrease in net emissions in Latin America since 2005 linked to reduced gross deforestation emissions, and a small increase in net emissions related to increased gross deforestation emissions in

Africa since 2000 (Figure 7.5). There is *high confidence* regarding the net AFOLU CO_2 sink in Europe due to forest regrowth and known other sinks in managed forests, and *medium confidence* of a net sink in North America and Eurasia since 2010.

7.2.2.2 Why do various methods deliver difference in results?

The processes responsible for fluxes from land have been divided into three categories (IPCC 2006, 2010): (1) the *direct human-induced effects* due to changing land cover and land management; (2) the *indirect human-induced effects* due to anthropogenic environmental change, such as climate change, CO_2 fertilisation, nitrogen deposition, etc.; and (3) *natural effects,* including climate variability and a background natural disturbance regime (e.g. wildfires, windthrows, diseases or insect outbreaks).

Global models estimate the anthropogenic land CO_2 flux considering only the impact of direct effects, and only those areas that were subject to intense and direct management such as clear-cut harvest. It is important to note, that DGVMs also estimate the non-anthropogenic land CO_2 flux (Land Sink) that results from indirect and natural effects (Table 7.1). In contrast, estimates of the anthropogenic land CO_2 flux in NGHGIs (LULUCF) include the impact of direct effects and, in most cases, of indirect effects on a much greater area considered "managed" than global models (Grassi et al. 2021).

The approach used by countries follows the IPCC methodological guidance for NGHGIs (IPCC 2006, 2019a). Since separating direct, indirect and natural effects on the land CO_2 sink is impossible with direct observation such as national forest inventories (IPCC 2010), upon which most NGHGIs are based, the IPCC adopted the 'managed land' concept as a pragmatic proxy to facilitate NGHGI reporting. Anthropogenic land GHG fluxes (direct and indirect effects) are defined as all those occurring on managed land, that is, where human interventions and practices have been applied to perform production, ecological or social functions (IPCC 2006, 2019a). GHG fluxes from unmanaged land are not reported in NGHGIs because they are assumed to be non-anthropogenic. Countries report NGHGI data with a range of methodologies, resolution and completeness, dependent on capacity and available data, consistent with IPCC guidelines (IPCC 2006, 2019a) and subject to an international review or assessment processes.

The FAOSTAT approach is conceptually similar to NGHGIs. FAOSTAT data on forests are based on country reports to FAO-FRA 2020 (FAO 2020a), and include changes in biomass carbon stock in "forest land" and "net forest conversions" in five-year intervals. "Forest land" may include unmanaged natural forest, leading to possible overall overestimation of anthropogenic fluxes for both sources and sinks, though emissions from deforestation are likely underestimated (Tubiello et al. 2020). FAOSTAT also estimate emissions from forest fires and other land uses (organic soils), following IPCC methods (Prosperi et al. 2020). The FAO-FRA 2020 (FAO 2020b) update leads to estimates of larger sinks in Russia since 1991, and in China and the USA from 2011, and larger deforestation emissions in Brazil and smaller in Indonesia than FRA 2015 (FAO 2015;Tubiello et al. 2020).

The bookkeeping models by Houghton and Nassikas (2017), Hansis et al. (2015), and Gasser et al. (2020) and the DGVMs used in the Global Carbon Budget (Friedlingstein et al. 2020) use either the LUH2 data set (Hurtt et al. 2020) HYDE (Goldewijk et al. 2017) FRA 2015 (FAO 2015) or a combination. The LUH2 dataset includes a new wood harvest reconstruction, new representation of shifting cultivation, crop rotations, and management information including irrigation and fertilizer application. The area of forest subject to harvest in LUH2 is much less than the area of forest considered "managed" in the NGHGIs (Grassi et al. 2018). The model datasets do not yet include the FAO FRA 2020 update (FAO 2020a). The DGVMs consider CO_2 fertilization effects on forest growth that are sometimes confirmed from the groundbased forest inventory networks (Nabuurs et al. 2013) and sometimes not at all (van der Sleen et al. 2015).

Further, the DGVMs and bookkeeping models do not include a wide range of practices which are implicitly covered by the inventories; for example: forest dynamics (Pugh et al. 2019; Le Noë et al. 2020) forest management including wood harvest (Nabuurs, et al. 2013; Arneth et al. 2017) agricultural and grassland practices (Pugh et al. 2015; Sanderman et al. 2017; Pongratz et al. 2018); or e.g. fire management (Andela et al. 2017; Arora and Melton 2018).

Increasingly higher emissions estimates are expected from DGVMs compared to bookkeeping models, because DGVMs include a loss of additional sink capacity of 3.3 ± 1.1 $GtCO_2$ yr^{-1} on average over 2009-2018, which is increasing with larger climate and CO_2 impacts (Friedlingstein et al. 2020). This arises because the DGVM methodological setup requires a reference simulation including climate and environmental changes but without any land use change such as deforestation, so DGVMs implicitly include the sink capacity forests would have developed in response to environmental changes on areas that in reality have been cleared (Gitz and Ciais 2003; Pongratz et al. 2014)(IPCC WGI Chapter 5).

Carbon emissions from peat burning have been estimated based on the Global Fire Emission Database (GFED4s; Van Der Werf et al. 2017). These were included in the bookkeeping model estimates and added 2.0 Gt Carbon over 1960-2019 (e.g. causing the peak in South-East Asia in 1998, Figure 7.5). Within the Global Carbon Budget (Friedlingstein et al. 2020), peat drainage from agriculture accounted for an additional 8.6 Gt Carbon from 1960-2019 according to FAOSTAT (Conchedda and Tubiello, 2020) used by two of the bookkeeping models, (Hansis et al. 2015; Gasser et al. 2020).

Remote-sensing products provide valuable spatial and temporal land-use and biomass data globally (including in remote areas), at potentially high spatial and temporal resolutions, that can be used to calculate CO_2 fluxes, but have mostly been applied only to forests at the global or even regional scale. While such data can strongly support monitoring reporting and verification, estimates of forest carbon fluxes directly from Earth Observation (EO) data vary considerably in both their magnitude and sign (i.e. whether forests are a net source or sink of carbon). For the period 2005 – 2017, net tropical forest carbon fluxes were estimated as -0.4 $GtCO_2$ yr^{-1} (Fan et al. 2019); 0.58 $GtCO_2$ yr^{-1} (Grace et al. 2014); 1.6 $GtCO_2 yr^{-1}$ (Baccini et al. 2017) and 2.87 $GtCO_2$ yr^{-1} (Achard et al. 2014). Differences can in part be explained by spatial resolution of the data sets, the definition of "forest" and the inclusion of processes and methods used to determine degradation and growth in intact and secondary forests, or the changes in algorithm over time (Palahí et al. 2021). A recent global study integrated ground observations and remote sensing data to map forest-related GHG emissions and removals at a high spatial resolution (30m spatial scale), although it only provides an average estimate of annual carbon loss over 2001–2019 (Harris et al. 2021). The estimated net global forest carbon sink globally was -7.66 $GtCO_2$ yr^{-1}, being -1.7 $GtCO_2 yr^{-1}$ in the tropics only.

Remote sensing products can help to attribute changes to anthropogenic activity or natural inter-annual climate variability (Fan et al. 2019; Wigneron et al. 2020). Products with higher spatial resolution make it easier to determine forest and carbon dynamics in relatively small-sized managed forests (e.g. Wang et al. 2020; Heinrich et al. 2021; Reiche et al. 2021). For example secondary forest regrowth in the Brazilian Amazon offset 9 to 14% of gross emissions due to deforestation [1] (Silva Junior et al. 2021; Aragão et al. 2018). Yet disturbances such as fire and repeated deforestation cycles due to shifting cultivation over the period 1985 to 2017, were found to reduce the regrowth rates of secondary forests by 8 to 55% depending on the climate region of regrowth (Heinrich et al. 2021).

7.2.2.3 Implications of differences in AFOLU CO_2 fluxes between global models and National Greenhouse Gas Inventories (NGHGIs), and reconciliation

There is about 5.5 $GtCO_2\ yr^{-1}$ difference in the anthropogenic AFOLU estimates between NGHGIs and global models (this number relates to an IAMs comparison for the period 2005-2015 - see Cross-Chapter Box 6 in this Chapter; for comparison with other models see Figure 7.4). Reconciling the differences i.e. making estimates comparable, can build confidence in land-related CO_2 estimates, for example for the purpose of assessing collective progress in the context of the Global Stocktake (Cross-Chapter Box 6 in this Chapter). The difference largely results from greater estimated CO_2 in NGHGIs, mostly occurring in forests (Grassi et al. 2021). This difference is potentially a consequence of: (i) simplified and/or incomplete representation of management in global models (Popp et al. 2017; Pongratz et al. 2018), e.g. concerning impacts of forest management in biomass expansion and thickening (Nabuurs et al. 2013; Grassi et al. 2017) (ii) inaccurate and/or incomplete estimation of LULUCF fluxes in NGHGIs (Grassi et al. 2017), especially in developing countries, primarily in non-forest land uses and in soils, and (iii) conceptual differences in how global models and NGHGIs define 'anthropogenic' CO_2 flux from land (Grassi et al. 2018). The impacts of (i) and (ii) are difficult to quantify and result in uncertainties that will decrease slowly over time through improvements of both models and NGHGIs. By contrast, the inconsistencies in (iii) and its resulting biases were assessed as explained below.

Since changing the NGHGIs' approach is impractical, an interim method to translate and adjust the output of global models was outlined for reconciling a bookkeeping model and NGHGIs (Grassi et al. 2018). More recently, an improved version of this approach has been applied to the future mitigation pathways estimated by IAMs (Grassi et al. 2021), with the implications for the Global Stocktake discussed in Cross-Chapter Box 6 in this Chapter. This method implies a post-processing of current global models' results that addresses two components of the conceptual differences in the "anthropogenic" CO_2 flux; (i) how the impact of human-induced environmental changes (indirect effects) are considered, and (ii) the extent of forest area considered 'managed'. Essentially, this approach adds DGVM estimates of CO_2 fluxes due to indirect effects from countries' managed forest area (using non-intact forest area maps as a proxy) to the original global models' anthropogenic land CO_2 fluxes (Figure 7.6).

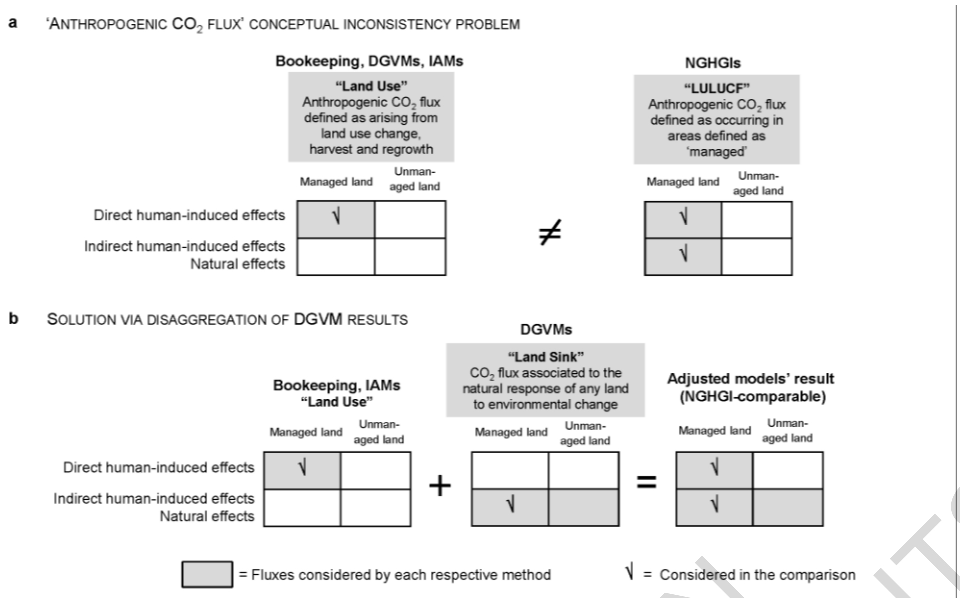

Figure 7.6 Main conceptual differences between global models (bookkeeping models, IAMs and DGVMs) and NGHGIs definitions of what is considered the 'anthropogenic' land CO_2 flux, and proposed solution (from Grassi et al. 2021). (Panel a) Differences in defining the anthropogenic land CO_2 flux by global models ('Land Use') and NGHGIs ('LULUCF'), including the attribution of processes responsible for land fluxes (IPCC 2006; 2010) in managed and unmanaged lands. The anthropogenic land CO_2 flux by global models typically includes only the CO_2 flux due to 'direct effects' (land-use change, harvest, regrowth). By contrast, most NGHGIs consider anthropogenic all fluxes occurring in areas defined as 'managed', including also the sink due to 'indirect effects' (climate change, atmospheric CO_2 increase, N deposition etc.) and due to 'natural effects' (climate variability, background natural disturbances). (Panel b) Proposed solution to the inconsistency, via disaggregation of the 'Land Sink' flux from DGVMs into CO_2 fluxes occurring in managed and in unmanaged lands. The sum of 'Land Use' flux (direct effects from bookkeeping models or IAMs) and the 'Land Sink' (indirect effects from DGVMs) in managed lands produces an adjusted global model CO_2 flux which is conceptually more comparable with LULUCF fluxes from NGHGIs. Note that the figure may in some cases be an oversimplification, e.g. not all NGHGIs include all recent indirect effects.

START CROSS-CHAPTER BOX 6 HERE

Cross-Chapter Box 6 Implications of reconciled anthropogenic land CO_2 fluxes for assessing collective climate progress in the global stocktake

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The Global Stocktake aims to assess countries' collective progress towards the long-term goals of the Paris Agreement in the light of the best available science. Historic progress is assessed based on NGHGIs, while expectations of future progress are based on country climate targets (e.g., NDCs for 2025 or 2030 and long-term strategies for 2050). Scenarios consistent with limiting warming well-below 2°C and 1.5°C developed by IAMs (Chapter 3) are expected to play a key role as benchmarks against which countries' aggregated future mitigation pledges will be assessed. This, however, implies that estimates by IAMs and country data used to measure progress are comparable.

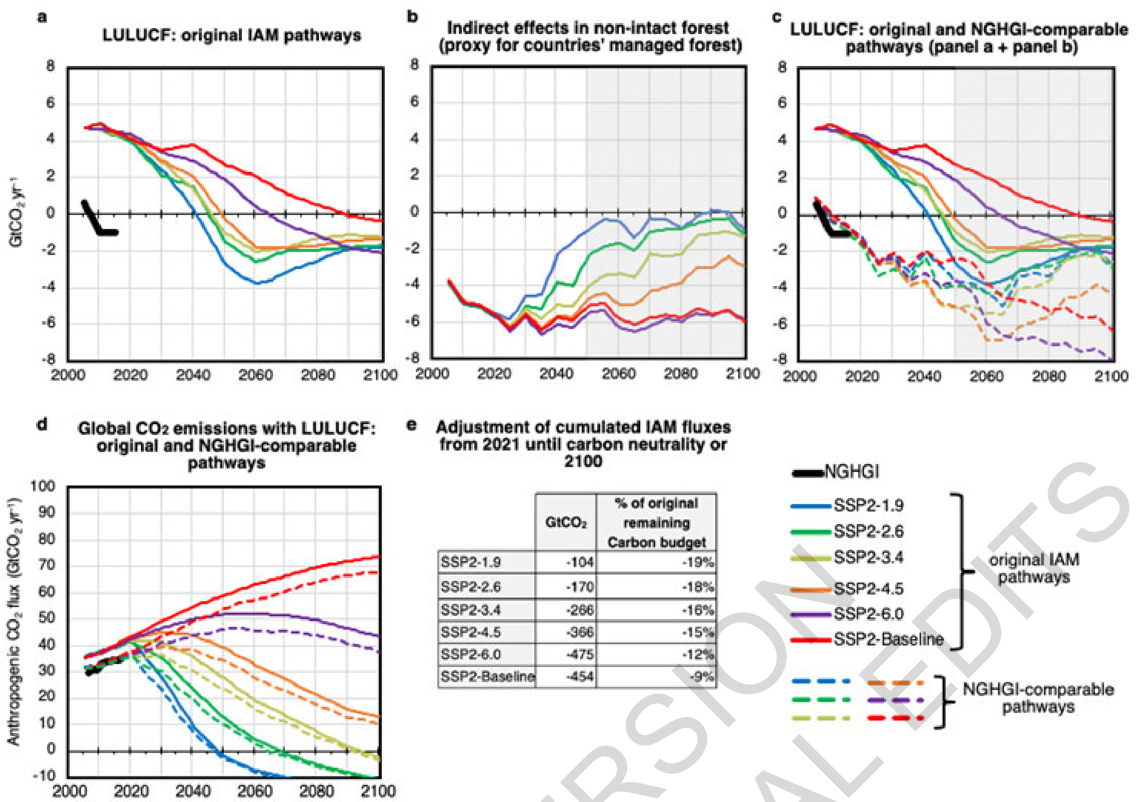
In fact, there is ~5.5 $GtCO_2$ yr^{-1} difference during 2005-2015 between global anthropogenic land CO_2 net flux estimates of IAMs and aggregated NGHGIs, due to different conceptual approaches to what is "anthopogenic". This approach and its implications when comparing climate targets with global mitigation pathways are illustrated in this Box Figure 1a-e.

By adjusting the original IAM output (Cross-Chapter Box 6, Figure 1a) with the indirect effects from countries' managed forest (Cross-Chapter Box 6, Figure 1b, estimated by DGVMs, see also Figure 7.6), NGHGI-comparable pathways can be derived (Cross-Chapter Box 6, Figure 1c). The resulting apparent increase in anthropogenic sink reflects simply a reallocation of a CO_2 flux previously labelled as natural, and thus does not reflect a mitigation action. These changes do not affect non-LULUCF emissions. However, since the atmosphere concentration is a combination of CO_2 emissions from LULUCF and from fossil fuels, the proposed land-related adjustments also influence the NGHGI-comparable economy-wide (all sector) CO_2 pathways (Cross-Chapter Box 6 Figure 1d).

This approach does not imply a change in the original decarbonisation pathways, nor does it suggest that indirect effects should be considered in the mitigation efforts. It simply ensures that a like-with-like comparison is made: if countries' climate targets use the NGHGI definition of anthropogenic emissions, this same definition can be applied to derive NGHGI-comparable future CO_2 pathways. This would have an impact on the NGHGI-comparable remaining carbon or GHG budget (i.e. the allowable emissions until net zero CO_2 or GHG emissions consistent with a certain climate target). For example, for SSP2-1.9 and SSP2-2.6 (representing pathways in line with 1.5°C and well-below 2°C limits under SSP2 assumptions), carbon budget is lower by -170 carbon $GtCO_2$-eq than the original remaining carbon budget according to the models' approach (Cross-Chapter Box 6, Figure 1e). Similarly, the remaining carbon (or GHG) budgets in Chapter 3 (this report), as well as the net zero carbon (or GHG) targets, could only be used in combination with the definition of anthropogenic emissions as used by the IAMs (Cross-Chapter Box 3 in Chapter 3). In the absence of these adjustments, collective progress would appear better than it is.

The UNEP's annual assessment of the global 2030 'emission gap' between aggregated country NDCs and specific target mitigation pathways (UNEP 2020), is only affected to a limited degree. This is because some estimates of global emissions under the NDCs already use the same land-use definitions as the IAM mitigation pathways (Rogelj et al. 2017), and because historical data of global NDC estimates is typically harmonised to the historical data of global mitigation pathway projections (Rogelj et al. 2011). This latter procedure, however, is agnostic to the reasons for the observed mismatch, and often uses a constant offset. The adjustment described here allows this mismatch to be resolved by drawing on a scientific understanding of the underlying reasons, and thus provides a more informed and accurate basis for estimating the emission gap.

The approach to deriving a NGHGI-comparable emission pathways presented here can be further refined with improved estimates of the future forest sink. Its use would enable a more accurate assessment of the collective progress achieved and of mitigation pledges under the Paris Agreement.



	$GtCO_2$	% of original remaining Carbon budget
SSP2-1.9	-104	-19%
SSP2-2.6	-170	-18%
SSP2-3.4	-266	-16%
SSP2-4.5	-366	-15%
SSP2-6.0	-475	-12%
SSP2-Baseline	-454	-9%

Cross-Chapter Box 6, Figure 1. Impact on global mitigation pathways of adjusting the modelled anthropogenic land CO_2 fluxes to be comparable with National Greenhouse Gas Inventories (NGHGIs) (from Grassi et al. 2021). Panel a: The mismatch between global historical LULUCF CO_2 net flux from NGHGIs (black), and the original (un-adjusted) modelled flux historically and under future mitigation pathways for SSP2 scenarios from Integrated Assessment Models (IAMs, Chapter 3). Panel b: fluxes due to indirect effects of environmental change on areas equivalent to countries' managed forest (i.e. those fluxes generally considered 'anthropogenic' by countries and 'natural' by global models). Panel c: original modelled (solid line) LULUCF mitigation pathways adjusted to be NGHGI-comparable (dashed line) i.e. by adding the indirect effects in panel b. The indirect effects in panel b decline over time with increasing mitigation ambition, mainly because of the weaker CO_2 fertilisation effect. In Panel c, the dependency of the adjusted LULUCF pathways on the target becomes less evident after 2030, because the indirect effects in countries' managed forest (which are progressively more uncertain with time, as highlighted by the grey areas) compensate the effects of the original pathways. Panel d: NGHGI-comparable pathways for global CO_2 emissions from all sectors including LULUCF (obtained by combining global CO_2 pathways without LULUCF - where no adjustment is needed - and the NGHGI-comparable CO_2 pathways for LULUCF (Gütschow et al. 2019; Grassi et al. 2017). Panel e: Cumulative impact of the adjustments from 2021 until net zero CO_2 emissions or 2100 (whatever comes first) on the remaining carbon budget.

END CROSS-CHAPTER BOX 6 HERE

7.2.3 CH_4 and N_2O flux from AFOLU

Trends in atmospheric CH_4 and N_2O concentrations and the associated sources, including land and land use are discussed in Sections 5.2.2 and 5.2.3 of the IPCC WGI sixth assessment report. Regarding AFOLU, the SRCCL and AR5 (Jia et al. 2019; Smith et al. 2014) identified three global non-CO_2 emissions data sources; EDGAR (Crippa et al. 2021), FAOSTAT (FAO 2021a; Tubiello, 2019) and the USA EPA (USEPA 2019). Methodological differences have been previously discussed (Jia et al. 2019).

In accordance with Chapter 2, this report, EDGAR data are used in Table 7.1 and Figure 7.3. It is important to note that in terms of AFOLU sectoral CH_4 and N_2O emissions, only FAOSTAT provides data on AFOLU emissions, while EDGAR and USEPA data consider just the agricultural component. However, the mean of values across the three databases for both CH_4 and N_2O, fall within the assessed uncertainty bounds (30 and 60% for CH_4 and N_2O respectively, Section 2.2.1, this report) of EDGAR data. NGHGIs annually submitted to the UNFCCC (Section 7.2.2.3) provide national AFOLU CH_4 and N_2O data, as included in the SRCCL (Jia et al. 2019). Aggregation of NGHGIs to indicate global emissions must be considered with caution, as not all countries compile inventories, nor submit annually. Additionally, NGHGIs may incorporate a range of methodologies for CH_4 and N_2O accounting (e.g. Thakuri et al. 2020; Ndung'U et al. 2019; Van der Weerden et al. 2016), making comparison difficult. The analysis of complete AFOLU emissions presented here, is based on FAOSTAT data. For agricultural specific discussion, analysis considers EDGAR, FAOSTAT and USEPA data.

7.2.3.1 Global AFOLU CH_4 and N_2O emissions

Using FAOSTAT data, the SRCCL estimated average CH_4 emissions from AFOLU to be 161.2 ± 43 Mt CH_4 yr^{-1} for the period 2007-2016, representing 44% of total anthropogenic CH_4 emissions, with agriculture accounting for 88% of the AFOLU component (Jia et al. 2019). The latest data (FAO 2021a, 2020b) highlight a trend of growing AFOLU CH_4 emissions, with a 10% increase evident between 1990 and 2019, despite year-to-year variation. Forestry and other land use (FOLU) CH_4 emission sources include biomass burning on forest land and combustion of organic soils (peatland fires) (FAO 2020c). The agricultural share of AFOLU CH_4 emissions remains relatively unchanged, with the latest data indicating agriculture to have accounted for 89% of emissions on average between 1990 and 2019. The SRCCL reported with *medium evidence* and *high agreement* that ruminants and rice production were the most important contributors to overall growth trends in atmospheric CH_4 (Jia et al. 2019). The latest data confirm this in terms of agricultural emissions, with agreement between databases that agricultural CH_4 emissions continue to increase and that enteric fermentation and rice cultivation remain the main sources (Figure 7.7). The proportionally higher emissions from rice cultivation indicated by EDGAR data compared to the other databases, may result from the use of a Tier 2 methodology for this source within EDGAR (Janssens-Maenhout et al. 2019).

The SRCCL also noted a trend of increasing atmospheric N_2O concentration, with *robust evidence* and *high agreement* that agriculture accounted for approximately two-thirds of overall global anthropogenic N_2O emissions. Average AFOLU N_2O emissions were reported to be 8.7 ± 2.5 Mt N_2O yr^{-1} for the period 2007-2016, accounting for 81% of total anthropogenic N_2O emissions, with agriculture accounting for 95% of AFOLU N_2O emissions (Jia et al. 2019). A recent comprehensive review confirms agriculture as the principal driver of the growing atmospheric N_2O concentration (Tian et al. 2020). The latest FAOSTAT data (FAO 2020b, 2021a) document a 25% increase in AFOLU N_2O emissions between 1990 and 2019, with the average share from agriculture remaining approximately the same (96%). Agricultural soils were identified in the SRCCL and in recent literature as a dominant emission source, notably due to nitrogen fertiliser and manure applications to croplands, and manure production and deposition on pastures (Jia et al. 2019; Tian et al. 2020). There is agreement within latest data that agricultural soils remain the dominant source (Figure 7.7).

Aggregation of CH_4 and N_2O to CO_2 equivalence (using GWP_{100} IPCC AR6 values), suggests that AFOLU emissions increased by 15% between 1990 and 2019, though emissions showed trend variability year to year. Agriculture accounted for 91% of AFOLU emissions on average over the period (FAO 2020b, 2021a). EDGAR (Crippa et al. 2021), FAOSTAT (FAO 2021a) and USEPA (USEPA 2019) data suggest aggregated agricultural emissions (CO_2-eq) to have increased since 1990, by 19

(1990-2019), 15 (1990-2019) and 21 (1990-2015) % respectively, with all databases identifying enteric fermentation and agricultural soils as the dominant agricultural emissions sources.

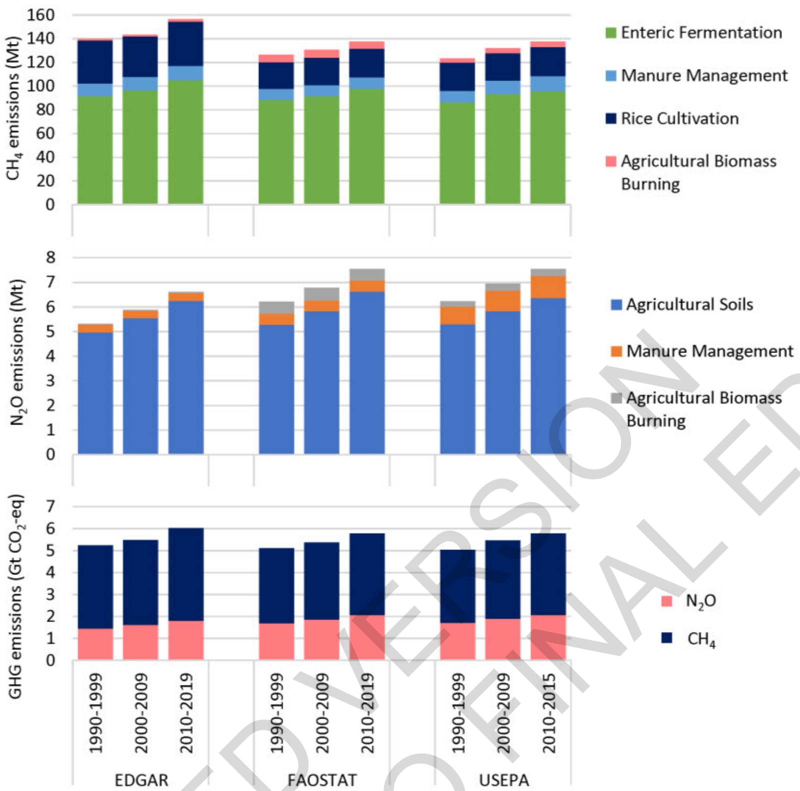


Figure 7.7 Estimated global mean agricultural CH_4 (Top), N_2O (Middle) and aggregated CH_4 and N_2O (using CO_2-eq according to GWP_{100} AR6 values) (Bottom) emissions for three decades according to EDGARv6.0 (Crippa et al. 2021), FAOSTAT (FAO 2021a) and USEPA (USEPA 2019) databases. Latest versions of databases indicate historic emissions to 2019, 2019 and 2015 respectively, with average values for the post-2010 period calculated accordingly. For CH_4, emissions classified as 'Other Ag.' within USEPA data, are re-classified as 'Agricultural Biomass Burning'. Despite CH_4 emissions from agricultural soils also being included, this category was deemed to principally concern biomass burning on agricultural land and classified accordingly. For N_2O, emissions classified within EDGAR as direct and indirect emissions from managed soils, and indirect emissions from manure management are combined under 'Agricultural Soils'. Emissions classified by FOASTAT as from manure deposition and application to soils, crop residues, drainage of organic soils and synthetic fertilisers are combined under 'Agricultural Soils', while emissions reported as 'Other Ag.' under USEPA data are re-classified as 'Agricultural Biomass Burning'.

7.2.3.2 Regional AFOLU CH_4 and N_2O emissions

FAOSTAT data (FAO 2020b, 2021a) indicate Africa (+ 44%), followed by Southern Asia (+ 29%) to have the largest growth in AFOLU CH_4 emissions between 1990 and 2019 (Figure 7.8). Eurasia was characterised by notable emission reductions (--58%), principally as a result of a sharp decline (--63%)

between 1990 and 1999. The average agricultural share of AFOLU emissions between 1990 and 2019 ranged from 66% in Africa to almost 100% in the Middle East.

In agreement with AR5 (Smith et al. 2014), the SRCCL identified Asia as having the largest share (37%) of emissions from enteric fermentation and manure management since 2000, but Africa to have the fastest growth rate. Asia was identified as responsible for 89% of rice cultivation emissions, which were reported as increasing (Jia et al. 2019). Considering classification by ten IPCC regions, data suggest enteric fermentation to have dominated emissions in all regions since 1990, except in South-east Asia and Developing Pacific, where rice cultivation forms the principal source (FAO 2021; USEPA 2019). The different databases broadly indicate the same regional CH_4 emission trends, though the indicated absolute change differs due to methodological differences (Section 7.2.3.1). All databases indicate considerable emissions growth in Africa since 1990 and that this region recorded the greatest regional increases in emissions from both enteric fermentation and rice cultivation since 2010. Additionally, FAOSTAT data suggest that emissions from agricultural biomass burning account for a notably high proportion of agricultural CH_4 emissions in Africa (Figure 7.8).

The latest data suggest growth in AFOLU N_2O emissions in most regions between 1990 and 2019, with Southern Asia demonstrating highest growth (+ 74%) and Eurasia, greatest reductions (- 51%), the latter mainly a result of a 61% reduction between 1990 and 2000 (FAO 2020b, 2021a). Agriculture was the dominant emission source in all regions, its proportional average share between 1990 and 2019 ranging from 87% in Africa, to almost 100% in the Middle East (Figure 7.8).

The SRCCL provided limited discussion on regional variation in agricultural N_2O emissions but reported with *medium confidence* that certain regions (North America, Europe, East & South Asia) were notable sources of grazing land N_2O emissions (Jia et al. 2019). AR5 identified Asia as the largest source and as having the highest growth rate of N_2O emissions from synthetic fertilisers between 2000 and 2010 (Smith et al. 2014). Latest data indicate agricultural N_2O emission increases in most regions, though variation between databases prevents definitive conclusions on trends, with Africa, Southern Asia, and Eastern Asia suggested to have had greatest growth since 1990 according to EDGAR (Crippa et al. 2021), FAOSTAT (FAO 2021a) and USEPA (USEPA 2019) data respectively. However, all databases indicate that emissions declined in Eurasia and Europe from 1990 levels, in accordance with specific environmental regulations put in place since the late 1980s (Tubiello 2019; European Environment Agency 2020; Tian et al. 2020), but generally suggest increases in both regions since 2010.

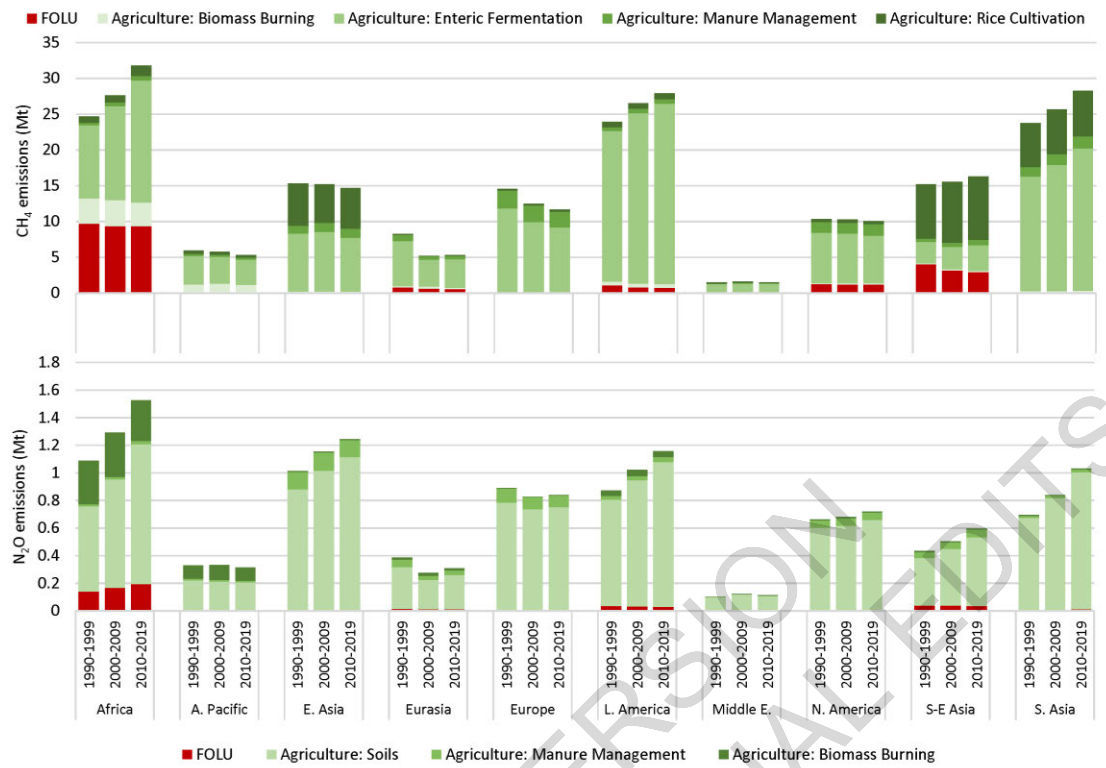


Figure 7.8 Estimated average AFOLU CH_4 (Top) and N_2O (Bottom) emissions for three decades according to FAOSTAT data by ten global regions, with disaggregation of agricultural emissions (FAO 2020b; 2021a). Note for N_2O, emissions from manure deposition and application to soils, crop residues and synthetic fertilisers are combined under 'Agricultural Soils'.

7.2.4 Biophysical effects and short-lived climate forcers

Despite new literature, general conclusions from the SRCCL and WGI-AR6 on biophysical effects and short-lived climate forcers remain the same. Changes in land conditions from land cover change or land management jointly affect water, energy, and aerosol fluxes (biophysical fluxes) as well as GHG fluxes (biogeochemical fluxes) exchanged between the land and atmosphere (*high agreement, robust evidence*) (Erb et al. 2017; Alkama and Cescatti 2016; Naudts et al. 2016; O'Halloran et al. 2012; Anderson et al. 2011). There is *high confidence* that changes in land condition do not just have local impacts but also have non-local impacts in adjacent and more distant areas (Mahmood et al. 2014; Pielke et al. 2011) which may contribute to surpassing climate tipping points (Brando et al. 2014; Nepstad et al. 2008). Non-local impacts may occur through: GHG fluxes and subsequent changes in radiative transfer, changes in atmospheric chemistry, thermal, moisture and surface pressure gradients creating horizontal transport (advection) (De Vrese et al. 2016; Davin and de Noblet-Ducoudre 2010) and vertical transport (convection and subsidence) (Devaraju et al. 2018). Although regional and global biophysical impacts emerge from model simulations (Devaraju et al. 2018; De Vrese et al. 2016; Davin and de Noblet-Ducoudre 2010), especially if the land condition has changed over large areas, there is *very low agreement* on the location, extent and characteristics of the non-local effects across models.

Recent methodological advances, empirically confirmed changes in temperature and precipitation owing to distant changes in forest cover (Meier et al. 2021; Cohn et al. 2019).

Following changes in land conditions, CO_2, CH_4 and N_2O fluxes are quickly mixed into the atmosphere and dispersed, resulting in the biogeochemical effects being dominated by the biophysical effects at local scales (*high confidence*) (Alkama and Cescatti 2016; Li et al. 2015). Afforestation/reforestation (Strandberg and Kjellström 2019; Lejeune et al. 2018), urbanisation (Li and Bou-Zeid 2013) and irrigation (Thiery et al. 2017; Mueller et al. 2016) modulate the likelihood, intensity, and duration of many extreme events including heatwaves (*high confidence*) and heavy precipitation events (*medium confidence*) (Haberlie et al. 2015). There is *high confidence and high agreement* that afforestation in the tropics (Perugini et al. 2017), irrigation (Mueller et al. 2016; Alter et al. 2015) and urban greening result in local cooling, *high agreement and medium confidence* on the impact of tree growth form (deciduous vs. evergreen) (Schwaab et al. 2020; Luyssaert et al. 2018; Naudts et al. 2016), and *low agreement* on the impact of wood harvest, fertilisation, tillage, crop harvest, residue management, grazing, mowing, and fire management on the local climate.

Studies of biophysical effects have increased since AR5 reaching *high agreement* for the effects of changes in land condition on surface albedo (Leonardi et al. 2015). *Low confidence* remains in proposing specific changes in land conditions to achieve desired impacts on local, regional and global climates due to: a poor relationship between changes in surface albedo and changes in surface temperature (Davin and de Noblet-Ducoudre 2010), compensation and feedbacks among biophysical processes (Kalliokoski et al. 2020; Bonan 2016), climate and seasonal dependency of the biophysical effects (Bonan 2016), omittance of short-lived chemical forcers (Kalliokoski et al. 2020; Unger 2014), and study domains often being too small to document possible conflicts between local and non-local effects (Hirsch et al. 2018; Swann et al. 2012).

7.3 Drivers

Since AR5 several global assessments (IPBES 2018; NYDF Assessment Report. 2019; UN Environment 2019; IPCC 2019) and studies (e.g. Tubiello 2019; Tian et al. 2020) have reported on drivers (natural and anthropogenic factors that affect emissions and sinks of the land use sector) behind AFOLU emissions trends, and associated projections for the coming decades. The following analysis aligns with the drivers typology used by (IPBES (2019) and the Global Environmental Outlook (UN Environment 2019). Drivers are divided into direct drivers resulting from human decisions and actions concerning land use and land-use change, and indirect drivers that operate by altering the level or rate of change of one or more direct drivers. Although drivers of emissions in Agriculture and FOLU are presented separately, they are interlinked, operating in many complex ways at different temporal and spatial scales, with outcomes depending on their interactions. For example, deforestation in tropical forests is a significant component of sectorial emissions. A review of deforestation drivers' studies published between 1996 and 2013, indicated a wide range of factors associated with deforestation rates across many analyses and studies, covering different regions (Figure 7.9; Busch and Ferretti-Gallon 2017). Higher agricultural prices were identified as a key driver of deforestation, while law enforcement, area protection, and ecosystem services payments were found to be important drivers of reduced deforestation, while timber activity did not show a consistent impact

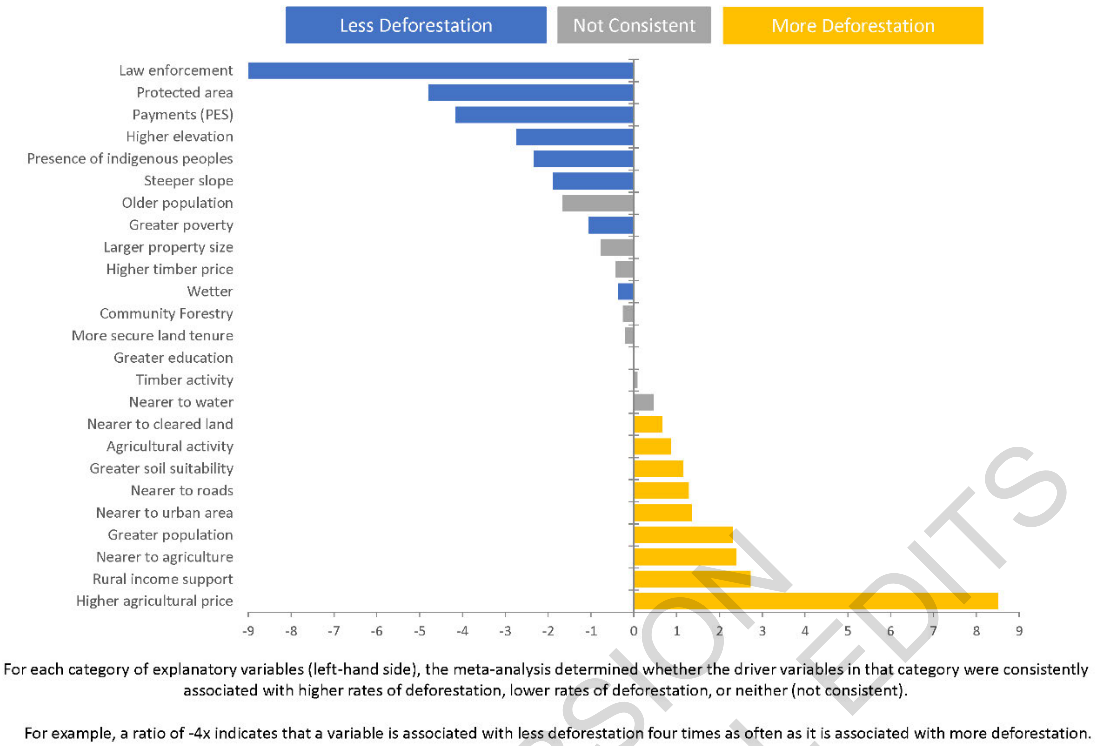


Figure 7.9 Association of driver variables with more or less deforestation
Source: Busch and Ferretti-Gallon (2017)

7.3.1 Anthropogenic direct drivers – Deforestation, conversion of other ecosystems, and land degradation

The global forest area in 2020 is estimated at 4.1 billion ha, representing 31% of the total land area (FAO 2020a). Most forests are situated in the tropics (45%), followed by boreal (27%), temperate (16%) and subtropical (11%) domains. Considering regional distribution of global forest area, Europe and the Russian Federation accounts for 25%, followed by South America (21%), North and Central America (19 %), Africa (16%), Asia (15%) and Oceania (5%). However, a significant share (54%) of the world's forest area concerns five countries – the Russian Federation, Brazil, Canada, the USA and China (FAO 2020a). Forest loss rates differ among regions though the global trend is towards a net forest loss (UN Environment 2019). The global forest area declined by about 178 Mha in the 30 years from 1990 to 2020 (FAO 2020a). The rate of net forest loss has decreased since 1990, a result of reduced deforestation in some countries and forest gains in others. The annual net loss of forest area declined from 7.8 Mha in 1990–2000, to 5.2 Mha in 2000–2010, to 4.7 Mha in 2010–2020, while the total growing stock in global forests increased (FAO 2020a). The rate of decline in net forest loss during the last decade was due mainly to an increase in the rate of forest gain (i.e. afforestation and the natural expansion of forests).

Globally, the area of the more open, other wooded land is also of significant importance, with almost 1 billion hectares (FAO 2020a). The area of other wooded land decreased by 30.6 Mha between 1990 and 2020 with larger declines between 1990–2000 (FAO 2020a). There are still significant challenges in monitoring the area of other wooded land, largely associated with difficulties in measuring tree-canopy cover in the range of 5–10%.The global area of mangroves, one of the most productive terrestrial ecosystems (Neogi 2020a), has also experienced a significant decline (Thomas et al. 2017; Neogi 2020b), with a decrease of 1.0 Mha between 1990 and 2020 (FAO 2020a) due to agriculture and aquaculture (Bhattarai 2011; Ajonina et al. 2014; Webb et al. 2014; Giri et al. 2015; Fauzi et al. 2019; Thomas et al. 2017). Some relevant direct drivers affecting emissions and removal in forests and other ecosystems are discussed in proceeding sections.

7.3.1.1. Conversion of natural ecosystems to agriculture

Previous IPCC reports identify land use change as an important driver of emissions and agriculture as a key driver of land use change, causing both deforestation and wetland drainage (Smith et al. 2019d). AR5 reported a trend of declining global agricultural land area since 2000 (Smith et al. 2014). The latest data (FAO 2021b) indicate a 2% reduction in the global agricultural area between 2000 and 2019 (Figure 7.10). This area includes (though is not limited to) land under permanent and temporary crops or pasture, temporary fallow and natural meadows and pasture utilized for grazing or agricultural purposes (FAO 2021b), although the extent of land used for grazing may not be fully captured (Fetzel et al. 2017). Data indicate changes in how agricultural land is used. Between 2000 and 2019, the area classified as permanent meadow and pasture decreased (- 6%) while cropland area (under arable production and temporary crops) increased (+ 2%). A key driver of this change has been a general trend of intensification, including in livestock production (Barger et al. 2018; OECD/FAO 2019; UN Environment 2019), whereby less grazing land is supporting increasing livestock numbers in conjunction with greater use of crops as livestock feed (Barger et al. 2018). The share of feed crops, such as maize and soybean, of global crop production is projected to grow as the demand for animal feed increases with further intensification of livestock production (OECD/FAO 2019). Despite increased demand for food, feed, fuel and fibre from a growing human population (FAO 2019b), global agricultural land area is projected to remain relatively stable during the next decade, with increases in production expected to result from agricultural intensification (OECD/FAO 2019).

Despite a decline in global agricultural area, the latest data document some regional expansion between 2000 and 2019, specifically in Africa (+ 3%) and Asia and the Developing Pacific (+ 1%). Agricultural area declined in all other regions, notably in developed countries (- 9%), due to multiple factors including among others, urbanisation (see Section 7.3.1.2).

7.3.1.2. Infrastructure development and urbanisation

Although built-up areas (defined as cities, towns, villages and human infrastructure) occupy a relatively small fraction of land (around 1% of global land), since 1975 urban clusters (i.e. urban centres as well as surrounding suburbs) have expanded approximately 2.5 times (UN Environment 2019; Chapter 8, this report). Regional differences are striking. Between 1975 and 2015, built-up areas doubled in size in Europe while urban population remained relatively constant. In Africa built-up areas grew approximately fourfold, while urban population tripled (UN Environment 2019). Trends indicate that rural-to-urban migration will continue and accelerate in developing countries increasing environmental pressure in spite of measures to mitigate some of the impacts (e.g. by preserving or enhancing natural systems within cities for example lakes or natural and urban green infrastructures (UN Environment 2019). If current population densities within cities remain stable, the extent of built-up areas in developed countries is expected to increase by 30% and triple in developing countries between 2000 and 2050 (Barger et al. 2018).

Urban expansion leads to landscape fragmentation and urban sprawl with effects on forest resources and land use (Ünal et al. 2019) while interacting with other drives. For example, in the Brazilian Amazon, the most rapid urban growth occurs within cities that are located near rural areas that produce commodities (minerals or crops) and are connected to export corridors (Richards and VanWey 2015). Urbanisation, coastal development and industrialisation also play crucial roles in the significant loss of mangrove forests (Richards and Friess 2016; Hirales-Cota 2010; Rivera-Monroy et al. 2017). Among infrastructural developments, roads are one of the most consistent and most considerable factors in deforestation, particularly in tropical frontiers (Pfaff et al. 2007; Rudel et al. 2009; Ferretti-Gallon and Busch 2014). The development of roads may also bring subsequent impacts on further development intensity due to increasing economic activities (see Chapter 8) mostly in the tropics and subtropics, where the expansion of road networks increases access to remote forests that act as refuges for biodiversity (Campbell et al. 2017) (Box 7.1). Logging is one of the main drivers of road construction in tropical forests (Kleinschroth and Healey 2017) which leads to more severe long term impacts that include increased fire incidence, soil erosion, landslides, and sediment accumulation in streams, biological invasions, wildlife poaching, illicit land colonisation, illegal logging and mining, land grabbing and land speculation (Laurance et al. 2009; Alamgir et al. 2017).

[START BOX 7.1 HERE]

Box 7.1 Case study: Reducing the impacts of roads on deforestation

Summary

Rapidly expanding roads, particularly in tropical regions, are linked to forest loss, degradation, and fragmentation because the land becomes more generally accessible. Increase of land values of areas adjacent to roads also drives speculation and deforestation related to land tenure (Fearnside 2015). If poorly planned, infrastructure can facilitate fires, illegal mining, and wildlife poaching with consequences for GHG emissions and biodiversity conservation. However, some initiatives are providing new approaches for better planning and then limit environmental and societal impacts**.**

Background

Although the number and extent of protected areas has increased markedly in recent decades (Watson et al. 2014), many other indicators reveal that nature is in broad retreat. For example, the total area of intact wilderness is declining rapidly worldwide (Watson et al. 2016), 70% of the world's forests are now less than 1 km from a forest edge (Haddad et al. 2015), the extent of tropical forest fragmentation is accelerating exponentially (Taubert et al. 2018). One of the most direct and immediate driver of deforestation and biodiversity decline is the dramatic expansion of roads and other transportation infrastructure (Laurance et al. 2014a; Laurance and Arrea 2017; Alamgir et al. 2017).

Case description

From 2010 to 2050, the total length of paved roads is projected to increase by 25 million km (Dulac 2013) including large infrastructure-expansion schemes in Asia (Lechner et al. 2018; Laurance and Arrea 2017) and in South America (Laurance et al. 2001; Killeen 2007)—as well as widespread illegal or unplanned road building (Barber et al. 2014; Laurance et al. 2009). For example, in the Amazon, 95% of all deforestation occurs within 5.5 km of a road, and for every km of legal road there are nearly three km of illegal roads (Barber et al. 2014).

Interactions and limitations

More than any other proximate factor, the dramatic expansion of roads is determining the pace and patterns of habitat disruption and its impacts on biodiversity (Laurance et al. 2009; Laurance and Arrea 2017). Much road expansion is poorly planned. Environmental Impact Assessments (EIAs) for roads and other infrastructure are typically too short-term and superficial to detect rare species or assess long-term or indirect impacts of projects (Flyvbjerg 2009; Laurance and Arrea 2017). Another limitation is the consideration of each project in isolation from other existing or planned developments (Laurance et al. 2014b). Hence, EIAs alone are inadequate for planning infrastructure projects and assessing their broader environmental, social, and financial impacts and risks (Laurance et al. 2015a; Alamgir et al. 2018, 2017).

Lessons

The large-scale, proactive land-use planning is an option for managing the development of modern infrastructure. Approaches such as the "Global Roadmap" scheme (Laurance and Balmford 2013; Laurance et al. 2014a) Strategic Environmental Assessments (Fischer 2007) can be used to evaluate the relative costs and benefits of infrastructure projects, and to spatially prioritise land-uses to optimise human benefits while limited new infrastructure in areas of intact or critical habitats. For example, the Global Roadmap strategy has been used in parts of Southeast Asia (Sloan et al. 2018), Indochina (Balmford et al. 2016), and sub-Saharan Africa (Laurance et al. 2015b) to devise land-use zoning that can help optimise the many risks and rewards of planned infrastructure projects.

[END BOX 7.1 HERE]

7.3.1.3. Extractive industry development

The extent and scale of mining is growing due to increased global demand (UN Environment 2019). Due to declining ore grades, more ore needs to be processed to meet demand, with extensive use of open cast mining. A low-carbon future may be more mineral intensive with for example, clean energy technologies requiring greater inputs in comparison to fossil-fuel-based technologies (Hund et al. 2020). Mining presents cumulative environmental impacts, especially in intensively mined regions (UN Environment 2019). The impact of mining on deforestation varies considerably across minerals and countries. Mining causes significant changes to the environment, for example through mining infrastructure establishment, soil erosion, urban expansion to support a growing workforce and development of mineral commodity supply chains (Sonter et al. 2015). The increasing consumption of gold in developing countries, increased prices, and uncertainty in financial markets is identified as driving gold mining and associated deforestation in the Amazon region (Alvarez-Berrios and Mitchell Aide 2015; Dezécache et al. 2017; Asner and Tupayachi 2017; Espejo et al. 2018). The total estimated area of gold mining throughout the region increased by about 40% between 2012 and 2016 (Asner and Tupayachi 2017). In the Brazilian Amazon, mining significantly increased forest loss up to 70 km beyond mining lease boundaries, causing 11,670 km^2 of deforestation between 2005 and 2015, representing 9% of all Amazon forest loss during this time (Sonter et al. 2015).

Mining is also an important driver of deforestation in African and Asian countries. In the Democratic Republic of Congo, where the second-largest area of tropical forest in the world occurs, mining-related deforestation exacerbated by violent conflict (Butsic et al. 2015). In India, mining has contributed to deforestation at a district level, with coal, iron and limestone having had the most adverse impact on forest area loss (Ranjan 2019). Gold mining is also identified as a driver of deforestation in Myanmar (Papworth et al. 2017).

7.3.1.4. Fire regime changes

Wildland fires account for approximately 70% of the global biomass burned annually (Van Der Werf et al. 2017) and constitute a large global source of atmospheric trace gases and aerosols (Gunsch et al. 2018; IPCC WGI AR6). Although fires are part of the natural system, the frequency of fires has increased in many areas, exacerbated by decreases in precipitation, including in many regions with humid and temperate forests that rarely experience large-scale fires naturally. Natural and human-ignited fires affect all major biomes, from peatlands through shrublands to tropical and boreal forests, altering ecosystem structure and functioning (Argañaraz et al. 2015; Engel et al. 2019; Mancini et al. 2018; Remy et al. 2017; Nunes et al. 2016; Aragão et al. 2018; (Rodríguez Vásquez et al. 2021).

However, the degree of incidence and regional trends are quite different and a study over 14 year indicated, on average, the largest fires in Australia, boreal North America and Northern Hemisphere Africa (Andela et al. 2019). More than half of the terrestrial surface of the Earth has fire regimes outside the range of natural variability, with changes in fire frequency and intensity posing major challenges for land restoration and recovery (Barger et al. 2018). In some ecosystems, fire prevention might lead to accumulation of large fuel loads that enable wildfires (Moreira et al. 2020a).

About 98 Mha of forest and savannahs are estimated to have been affected by fire in 2015 (FAO and UNEP 2020). Fire is a prevalent forest disturbance in the tropics where about 4% of the total forest and savannah area in that year was burned and more than two-thirds of the total area affected was in Africa and South America; mostly open savanna types (FAO and UNEP 2020). Fires have many different causes, with land clearing for agriculture the primary driver in tropical regions, for example, clearance for industrial oil-palm and paper-pulp plantations in Indonesia (Chisholm et al. 2016), or for pastures in the Amazon (Barlow et al. 2020). Other socioeconomic factors are also associated with wildfire regimes such as land-use conflict and socio-demographic aspects (Nunes et al. 2016; Mancini et al. 2018). Wildfire regimes are also changing by the influence of climate change, with wildfire seasons becoming longer, wildfire average size increases in many areas and wildfires occurring in areas where they did not occur before (Jolly et al. 2015; Artés et al. 2019). Human influence has likely increased fire weather in some regions of all inhabited continents (IPCC WGI AR6 Technical Summary) and, in the last years, fire seasons of unprecedented magnitude occurred in diverse regions as California (Goss et al. 2020), the Mediterranean basin (Ruffault et al. 2020), Canada (Kirchmeier-Young et al. 2019) with unprecedented fires in British Columbia in 2021, the Arctic and Siberia (McCarty et al. 2020), Brazilian Amazon (Silva et al. 2021b) and Pantanal (Leal Filho et al. 2021), Chile (Bowman et al. 2019) and Australia (Gallagher et al. 2021; Ward et al. 2020). Lightning plays an important role in the ignition of wildfires, with the incidence of lightning igniting wildfires predicted to increase with rises in global average air temperature (Worden et al. 2017).

7.3.1.5. Logging and fuelwood harvest

The area of forest designated for production has been relatively stable since 1990. Considering forest uses, about 30% (1.2 billion ha) of all forests is used primarily for production (wood and non-wood forest products), about 10% (424 Mha) is designated for biodiversity conservation, 398 Mha for the protection of soil and water, and 186 Mha is allocated for social services (recreation, tourism, education research and the conservation of cultural and spiritual sites) (FAO and UNEP 2020). While the rate of increase in the area of forest allocated primarily for biodiversity conservation has slowed in the last ten years, the rate of increase in the area of forest allocated for soil and water protection has grown since 1990, and notably in the last ten years. Global wood harvest (including from forests, other wooded land and trees outside forests) was estimated to be almost 4.0 billion m^3 in 2018 (considering both industrial roundwood and fuelwood) (FAO, 2019). Overall, wood removals are increasing globally as demand for, and the consumption of wood products grows annually by 1% in line with growing populations and incomes with this trend expected to continue in coming decades. When done in a sustainable way, more regrowth will occur and is stimulated by management, resulting in a net sink. However illegal and unsustainable logging (i.e. harvesting of timber in contravention of the laws and regulations of the country of harvest) is a global problem with significant negative economic (e.g. lost revenue), environmental (e.g. deforestation, forest degradation, GHG emissions and biodiversity losses) and social impact (e.g. conflicts over land and resources, disempowerment of local and indigenous communities) (World Bank 2019). Many countries around the world have introduced regulations for the international trade of forest products to reduce illegal logging, with significant and positive impacts (Guan et al. 2018).

Over-extraction of wood for timber and fuelwood) is identified as an important driver of mangrove deforestation and degradation (Fauzi et al. 2019; Bhattarai 2011; Ajonina et al. 2014; Webb et al. 2014; Giri et al. 2015; Thomas et al. 2017; Bhattarai 2011; Ajonina et al. 2014; Webb et al. 2014; Giri et al. 2015; Thomas et al. 2017; Fauzi et al. 2019). Unsustainable selective logging and over-extraction of wood is a substantial form of forest and mangrove degradation in many tropical and developing countries, with emissions associated with the extracted wood, incidental damage to the surrounding forest and from logging infrastructure (Pearson et al. 2014, (Fauzi et al. 2019; Bhattarai 2011; Ajonina et al. 2014; Webb et al. 2014; Giri et al. 2015; Thomas et al. 2017).). Traditional fuelwood and charcoal continue to represent a dominant share of total wood consumption in low-income countries (Barger et al. 2018). Regionally, the percentage of total wood harvested used as fuelwood varies from 90% in Africa, 62 % in Asia, 50% in South America to less than 20 % in Europe, North America and Oceania. Under current projections, efforts to intensify wood production in plantation forests, together with increases in fuel-use efficiency and electrification, are suggested to only partly alleviate the pressure on native forests (Barger et al. 2018). Nevertheless, the area of forest under management plans has increased in all regions since 2000 by 233 Mha (FAO-FRA 2020). In regions representing the majority of industrial wood production, forests certified under sustainable forest management programs accounted for 51% of total managed forest area in 2017, an increase from 11% in 2000 (ICFPA 2021).

7.3.2. Anthropogenic direct drivers – Agriculture

7.3.2.1. Livestock populations and management

Enteric fermentation dominates agricultural CH_4 emissions (Section 7.2.3) with emissions being a function of both ruminant animal numbers and productivity (output per animal). In addition to enteric fermentation, both CH_4 and N_2O emissions from manure management (i.e. manure storage and application) and deposition on pasture, make livestock the main agricultural emissions source (Tubiello 2019). AR5 reported increases in populations of all major livestock categories between the 1970s and 2000s, including ruminants, with increasing numbers directly linked with increasing CH_4 emissions (Smith et al. 2014). The SRCCL identified managed pastures as a disproportionately high N_2O emissions source within grazing lands, with *medium confidence* that increased manure production and deposition was a key driver (Jia et al. 2019). The latest data (FAO 2021c) indicate continued global livestock population growth between 1990 and 2019 (Figure 7.10), including increases of 18% in cattle and buffalo numbers, and 30% in sheep and goat numbers, corresponding with CH_4 emission trends. Data also indicate increased productivity per animal for example, average increases of 16% in beef, 17% in pig meat and 70% in whole (cow) milk per respective animal between 1990 and 2019 (FAO 2021c). Despite these advances leading to reduced emissions per unit of product (calories, meat and milk) (FAO 2016; Tubiello 2019), increased individual animal productivity generally requires increased inputs (e.g. feed) and this generates increased emissions (Beauchemin et al. 2020). Manipulation of livestock diets, or improvements in animal genetics or health may counteract some of this. In addition, the production of inputs to facilitate increased animal productivity, may indirectly drive further absolute GHG emissions along the feed supply chain.

Although there are several potential drivers (McDermott et al. 2010; Alary V. 2015), increased livestock production is principally in response to growth in demand for animal-sourced food, driven by a growing human population (FAO, 2019) and increased consumption resulting from changes in affluence, notably in middle-income countries (Godfray et al. 2018). Available data document increases in total meat and milk consumption by 24 and 22% respectively between 1990 and 2013, as indicated by average annual per capita supply (FAO 2017a). Updated data indicate that trends of increasing consumption continued between 2014 and 2018 (FAO 2021d). Sustained demand for animal-sourced food is expected to drive further livestock sector growth, with global production projected to expand by 14% by 2029, facilitated by maintained product prices and lower feed prices (OECD/FAO 2019).

7.3.2.2. Rice cultivation

In addition to livestock, both AR5 and the SRCCL identified paddy rice cultivation as an important emissions source (Smith et al. 2014), with *medium evidence* and *high agreement* that its expansion is a key driver of growing trends in atmospheric CH_4 concentration (Jia et al. 2019). The latest data indicate the global harvested area of rice to have grown by 11% between 1990 and 2019, with total paddy production increasing by 46%, from 519 Mt to 755 Mt (FAO 2021c). Global rice production is projected to increase by 13% by 2028 compared to 2019 levels (OECD/FAO 2019). However, yield increases are expected to limit cultivated area expansion, while dietary shifts from rice to protein as a result of increasing per capita income, is expected to reduce demand in certain regions, with a slight decline in related emissions projected to 2030 (USEPA 2019).

Between 1990 and 2019, Africa recorded the greatest increase (+160%) in area under rice cultivation, followed by Asia and the Developing Pacific (+6%), with area reductions evident in all other regions (FAO 2021c) broadly corresponding with related regional CH_4 emission (Figures 7.3 and 7.8). Data indicate the greatest growth in consumption (average annual supply per capita) between 1990 and 2013 to have occurred in Eastern Europe and West Central Asia (+ 42%) followed by Africa (+ 25%), with little change (+ 1%) observed in Asia and the Developing Pacific (FAO 2017a). Most of the projected increase in global rice consumption is in Africa and Asia (OECD/FAO 2019).

7.3.2.3. Synthetic fertiliser use

Both AR5 and the SRCCL described considerable increases in global use of synthetic nitrogen fertilisers since the 1970s, which was identified to be a major driver of increasing N_2O emissions (Jia et al. 2019). The latest data document a 41% increase in global nitrogen fertiliser use between 1990 and 2019 (FAO 2021e) corresponding with associated increased N_2O emissions (Figure 7.3). Increased fertiliser use has been driven by pursuit of increased crop yields, with for example, a 61% increase in average global cereal yield per hectare observed during the same period (FAO 2021c), achieved through both increased fertiliser use and varietal improvements. Increased yields are in response to increased demand for food, feed, fuel and fibre crops which in turn has been driven by a growing human population (FAO, 2019), increased demand for animal-sourced food and bioenergy policy (OECD/FAO 2019). Global crop production is projected to increase by almost 15% over the next decade, with low income and emerging regions with greater availability of land and labour resources expected to experience the strongest growth, and account for about 50% of global output growth (OECD/FAO 2019). Increases in global nitrogen fertiliser use are also projected, notably in low income and emerging regions (USEPA 2019).

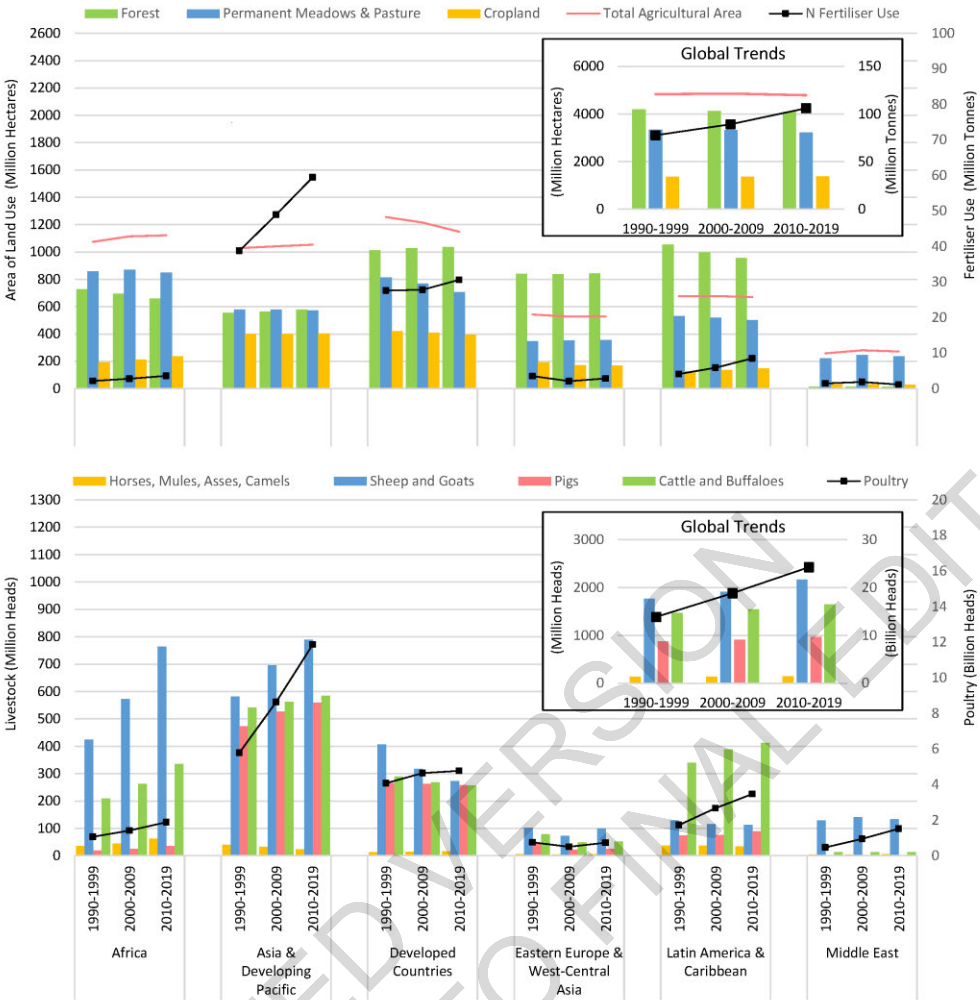


Figure 7.10 Trends in average global and regional land area under specific land uses (FAO 2021b), inorganic nitrogen fertiliser use (FAO 2021e) (Top) and number of livestock (FAO 2021c) (Bottom) for three decades. For land use classification 'cropland' represents the FAOSTAT category 'arable land' which includes land under temporary crops, meadow, pasture and fallow. 'Forest' and 'permanent meadow and pasture' follow FAOSTAT categories.

7.3.3. Indirect drivers

The indirect drivers behind how humans both use and impact natural resources are outlined in Table 7.2, specifically; demographic, economic and cultural, scientific and technological, and institutional and governance drivers. These indirect drivers not only interact with each other at different temporal and spatial scales but are also subject to impacts and feedbacks from the direct drivers (Barger et al. 2018).

Table 7.2 Indirect drivers of anthropogenic land and natural resource use patterns

Demography	***Global and regional trends in population growth:*** There was a 43% increase in global population between 1990 and 2018. The greatest growth was observed in Africa and the

	Middle East (+ 104%) and least growth in Eastern Europe and West-Central Asia (+ 7%) (FAO 2019b). ***Global and regional projections***: Population is projected to increase by 28% between 2018 and 2050 reaching 9.7 billion (FAO 2019). The world's population is expected to become older, more urbanised and live in smaller households (UN Environment 2019). ***Human migration:*** Growing mobility and population are linked to human migration, a powerful driver of changes in land and resource use patterns at decadal timescales, with the dominant flow of people being from rural areas to urban settlements over the past few decades, notably in the developing world (Adger et al. 2015; Barger et al. 2018).
Economic development and cultural factors	Changes in land use and management come from individual and social responses to economic opportunities (e.g. demand for a particular commodity or improved market access), mediated by institutions and policies (e.g. agricultural subsidies and low-interest credit or government-led infrastructure projects) (Barger et al. 2018). ***Projections on consumption***: If the future global population adopts a per capita consumption rate similar to that of the developed world, the global capacity to provide land-based resources will be exceeded (Barger et al. 2018). Economic growth in the developing world is projected to double the global consumption of forest and wood products by 2030, with demand likely to exceed production in many developing and emerging economies in Asia and Africa within the next decade (Barger et al. 2018). ***Global trade***: Market distorting agricultural subsidies and globalisation increases pressure on land systems and functions, with global trade and capital flow influencing land use, notably in developing countries (Yao et al. 2018; Furumo and Aide 2017; Pendrill et al. 2019a; (UN Environment 2019), OECD/FAO 2019). Estimates suggest that between 29 and 39% of emissions from deforestation in the tropics resulted from the international trade of agricultural commodities (Pendrill et al. 2019a).
Science and technology	Technological factors operates in conjunction with economic drivers of land use and management, whether through intensified farming techniques and biotechnology, high-input approaches to rehabilitating degraded land (e.g. Lin et al. 2017; Guo et al. 2020) or through new forms of data collection and monitoring (e.g. Song et al. 2018; Thyagharajan and Vignesh 2019; Arévalo et al. 2020). ***Changes in farming and forestry systems***: Changes can have both positive and negative impacts regarding multiple factors, including GHG emission trends. Fast advancing technologies shape production and consumption, and drive land-use patterns and terrestrial ecosystems at various scales. Innovation is expected to help drive increases in global crop production during the next decade (OECD/FAO 2019). For example, emerging gene editing technologies, may advance crop breeding capabilities, though are subject to biosafety, public acceptance and regulatory approval (Jaganathan et al. 2018; Chen et al. 2019; Schmidt et al. 2020). Technological changes were significant for the expansion of soybean in Brazil by adapting to different soils and photoperiods (Abrahão and Costa 2018). In Asia, technological development changed agriculture with significant improvements in production and adaptation to climate change (Thomson et al. 2019; Giller and Ewert 2019; Anderson et al. 2020; Cassman and Grassini 2020). Developments such as precision agriculture and drip irrigation have facilitated more efficient agrochemical and water use (UN Environment 2019). Research and development are central to forest restoration strategies that have become increasingly important around the world as costs vary depending on methods used, from natural regeneration with native tree species to active restoration using site preparation and planting (Löf et al. 2019). In addition, climate change poses the challenge about tree species selection in the future. Innovations in the forest sector innovations also form the basis of a bioeconomy associated with bioproducts and new processes (Verkerk et al. 2020; Cross-Working Group Box 3 in Chapter 12).

	Emerging mitigation technologies: Chemically synthesised methanogen inhibitors for ruminants are expected to be commercially available in some countries within the next two years and have considerable CH_4 mitigation potential (McGinn et al. 2019; Melgar et al. 2020; Beauchemin et al. 2020; Reisinger et al. 2021) (Section 7.4.3). There is growing literature (in both academic and non-academic sphere) on the biological engineering of protein. Although in its infancy and subject to investment, technological development, regulatory approval and consumer acceptance, it is suggested to have the potential to disrupt current livestock production systems and land use (Stephens et al. 2018; Ben-Arye and Levenberg 2019; Post et al. 2020; RethinkX 2019). The extent to which this is possible and the overall climate benefits are unclear (Lynch and Pierrehumbert 2019; Chriki and Hocquette 2020).
Institutions and governance	Institutional factors often moderate the relevance and impact of changes in economic and demographic variables related to resource exploitation and use. Institutions encompass the rule of law, legal frameworks and other social structures (e.g. civil society networks and movements) determining land management (e.g. formal and informal property rights, regimes and their enforcement); information and knowledge exchange systems; local and traditional knowledge and practice systems (Barger et al. 2018). ***Land rights***: Land tenure often allows communities to exercise traditional governance based on traditional ecological knowledge, devolved and dynamic access rights, judicious use, equitable distribution of benefits (Mantyka-Pringle et al. 2017; Wynberg 2017; Thomas et al. 2017), biodiversity (Contreras-Negrete et al. 2014) and fire and grazing management (Levang et al. 2015; Varghese et al. 2015). ***Agreements and Finance:*** Since AR5, global agreements were reached on climate change, sustainable development goals, and the mobilisation of finance for development and climate action. Several countries adopted policies and commitments to restore degraded land (Barger et al. 2018). The UN Environment Programme (UNEP) and the Food and Agriculture Organization of the UN (FAO), launched the UN Decade on Ecosystem Restoration (https://www.decadeonrestoration.org/). Companies have also made pledges to reduce impacts on forests and on the rights of local communities as well as eliminating deforestation from their supply chains. The finance sector, a crucial driver behind action (Section 7.6, Box 7.12), has also started to make explicit commitments to avoiding environmental damage (Barger et al. 2018) and net zero targets (Forest Trends Ecosystem Marketplace 2021), though investment is sensitive to market outlook.

7.4. Assessment of AFOLU mitigation measures including trade-offs and synergies

AFOLU mitigation or land-based climate change mitigation (used in this chapter interchangeably) are a variety of land management or demand management practices that reduce GHG emissions and/or enhance carbon sequestration within the land system (i.e. in forests, wetlands, grasslands, croplands and pasturelands). If implemented with benefits to human well-being and biodiversity, land-based mitigation measures are often referred to as nature-based solutions and/or natural climate solutions (Glossary). Measures that result in a net removal of GHGs from the atmosphere and storage in either living or dead organic material, or in geological stores, are known as CDR, and in previous IPCC reports were sometimes referred to as greenhouse gas removal (GGR) or negative emissions technologies (NETs) (Rogelj et al. 2018a; Jia et al. 2019). This section evaluates current knowledge and latest scientific literature on AFOLU mitigation measures and potentials, including land-based CDR measures. Section 7.4.1 provides an overview of the approaches for estimating mitigation potential, the co-benefits and risks from land-based mitigation measures, estimated global and regional mitigation potential and associated costs according to literature published over the last decade. Subsequent subsections assess literature on 20 key AFOLU mitigation measures specifically providing:

- A description of activities, co-benefits, risks and implementation opportunities and barriers
- A summary of conclusions in AR5 and IPCC Special Reports (SR15, SROCCC and SRCCL)
- An overview of literature and developments since the AR5 and IPCC Special Reports
- An assessment and conclusion based on current evidence

Measures are categorised as supply-side activities in: (1) forests and other ecosystems (Section 7.4.2), (2) agriculture (Section 7.4.3), (3) bioenergy and other land-based energy technologies (Section 7.4.4); as well as (4) demand-side activities (Section 7.4.5) (Figure 7.11). Several information boxes are dispersed within the section and provide supporting material, including case studies exploring a range of topics from climate-smart forestry in Europe (Box 7.2), agroforestry in Brazil (Box 7.3), climate-smart village approaches (Box 7.4), farm systems approaches (Box 7.5), mitigation within Indian agriculture (Box 7.6), and bioenergy and BECCS mitigation calculations (Box 7.7). Novel measures, including enhanced weathering and novel foods are covered in Chapter 12, this report. In addition, as mitigation within AFOLU concerns land management and use of land resources, AFOLU measures impact other sectors. Accordingly, AFOLU measures are also discussed in other sectoral chapters within this report, notably demand-side solutions (Chapter 5), bioenergy and Bioenergy with Carbon Capture and Storage (BECCS) (Chapter 6), the use of wood products and biomass in buildings (Chapter 9), and CDR measures, food systems and land related impacts, risks and opportunities of mitigation measures (Chapter 12).

7.4.1. Introduction and overview of mitigation potential

7.4.1.1. Estimating mitigation potentials

Mitigation potentials for AFOLU measures are estimated by calculating the scale of emissions reductions or carbon sequestration against a counterfactual scenario without mitigation activities. The types of mitigation potential estimates in recent literature include: (1) technical potential (the biophysical potential or amount possible with current technologies), (2) economic potential (constrained by costs, usually by a given carbon price (Table 7.3), (3) sustainable potential (constrained by environmental safeguards and/or natural resources, e.g. limiting natural forest conversion), and (4) feasible potential (constrained by environmental, socio-cultural, and/or institutional barriers), however, there are no set definitions used in literature. In addition to types of mitigation estimates, there are two

AFOLU mitigation categories often calculated: supply-side measures (land management interventions) and demand-side measures (interventions that require a change in consumer behaviour).

Two main approaches to estimating mitigation potentials include: 1) studies on individual measures and/or sectors – henceforth referred to as sectoral assessments, and 2) integrated assessment models (IAM). Sectoral assessments include studies focusing on one activity (e.g. agroforestry) based on spatial and biophysical data, as well as econometric and optimisation models for a sector, e.g. the forest or agriculture sector, and therefore cover a large suite of practices and activities while representing a broad body of literature. Sectoral assessments however, rarely capture cross-sector interactions or impacts, making it difficult to completely account for land competition, trade-offs, and double counting when aggregating sectoral estimates across different studies and methods (Smith et al. 2014; Jia et al. 2019). On the other hand, IAMs assess the climate impact of multiple and interlinked practices across sectors and therefore, can account for interactions and trade-offs (including land competition, use of other resources and international trade) between them. However, the number of land-based measures used in IAMs are limited compared with the sectoral portfolio (Figure 7.11). The resolution of land-based measures in IAMs are also generally coarser compared to some sectoral estimates, and as such, may be less robust for individual measures (Roe et al. 2021). Given the differences between and strengths and weaknesses of the two approaches, it is helpful to compare the estimates from both. We combine estimates from both approaches to establish an updated range of global land-based mitigation potential.

For the 20 land-based mitigation measures outlined in this section, the mitigation potential estimates are largely derived from sectoral approaches, and where data is available, are compared to IAM estimates. Integrated assessment models and the emissions trajectories, cost-effectiveness and trade-offs of various mitigation pathways are detailed in Section 7.5. It should be noted that the underlying literature for sectoral as well as IAM mitigation estimates consider GWP_{100} IPCC AR5 values (CH_4 = 28, N_2O = 265) as well as GWP_{100} IPCC AR4 values (CH_4 = 25, N_2O = 298) to convert CH_4 and N_2O to CO_2-eq. Where possible, we note the various GWP_{100} values (in IAM estimates, and the wetlands and agriculture sections), however in some instances, the varying GWP_{100} values used across studies prevents description of non-CO_2 gases in native units as well as conversion to AR6 GWP_{100} (CH_4 = 27, N_2O = 273) CO_2-eq values to aggregate sectoral assessment estimates.

7.4.1.2. Co-benefits and risks

Land interventions have interlinked implications for climate mitigation, adaptation, food security, biodiversity, ecosystem services, and other environmental and societal challenges (Section 7.6.5). Therefore, it is important to consider the net effect of mitigation measures for achieving both climate and non-climate goals (Section 7.1).

While it is helpful to assess the general benefits, risks and opportunities possible for land-based mitigation measures (Smith et al. 2019a), their efficacy and scale of benefit or risk largely depends on the type of activity undertaken, deployment strategy (e.g. scale, method), and context (e.g. soil, biome, climate, food system, land ownership) that vary geographically and over time (Smith et al. 2019a,b; Hurlbert et al. 2019; Chapter 12, Section 12.5) *(robust evidence, high agreement)*. Impacts of land-based mitigation measures are therefore highly context specific and conclusions from specific studies may not be universally applicable. If implemented at appropriate scales and in a sustainable manner, land-based mitigation practices have the capacity to reduce emissions and sequester billions of tonnes of carbon from the atmosphere over coming decades, while also preserving or enhancing biodiversity, water quality and supply, air quality, soil fertility, food and wood security, livelihoods, resilience to droughts, floods and other natural disasters, and positively contributing to ecosystem health and human wellbeing *(high confidence)* (Toensmeier 2016; Karlsson et al. 2020).

Overall, measures in the AFOLU sector are uniquely positioned to deliver substantial co-benefits.

However, the negative consequences of inappropriate or misguided design and implementation of measures may be considerable, potentially impacting for example, mitigation permanence, longevity, and leakage, biodiversity, wider ecosystem functioning, livelihoods, food security and human well-being (Section 7.6; WGII, Box 2.2. 'Risks of maladaptive mitigation'. Land-based mitigation may also face limitations and trade-offs in achieving sustained emission reductions and/or removals due to other land challenges including climate change impacts. It is widely recognised that land-use planning that is context-specific, considers other sustainable development goals, and is adaptable over time can help achieve land-based mitigation that maximises co-benefits, avoids or limits trade-offs, and delivers on international policy goals including the SDGs, Land Degradation Neutrality, and Convention on Biological Diversity (Section 7.6; Chapter 12).

Potential co-benefits and trade-offs are outlined for each of the 20 land-based mitigation measures in the proceeding sub-sections and summarised in Figure 7.12. Section 7.6.5. discusses general links with ecosystem services, human well-being and adaptation, while Chapter 12 (Section 12.5) provides an in-depth assessment of the land related impacts, risks and opportunities associated with mitigation options across sectors, including positive and negative effects on land resources, water, biodiversity, climate, and food security.

7.4.1.3. Overview of global and regional technical and economic potentials in AFOLU

IPCC AR5 (2014). In the AR5, the economic mitigation potential of supply-side measures in the AFOLU sector was estimated at 7.18–10.60 $GtCO_2$-eq yr^{-1} in 2030 with carbon prices up to USD100 tCO_2-eq^{-1}, about a third of which could be achieved at < USD20 tCO_2-eq^{-1} (*medium evidence; medium agreement*) (Smith et al. 2014). AR5 provided a summary table of individual AFOLU mitigation measures, but did not conduct a detailed assessment for each.

IPCC SRCCL (2019). The SRCCL assessed the full range of technical, economic and sustainability mitigation potentials in AFOLU for the period 2030-2050 and identified reduced deforestation and forest degradation to have greatest potential for reducing supply-side emissions (0.4–5.8 $GtCO_2$-eq yr^{-1}) (*high confidence*) followed by combined agriculture measures, 0.3–3.4 $GtCO_2$-eq yr^{-1} (*medium confidence*) (Jia et al. 2019). For the demand-side estimates, shifting towards healthy, sustainable diets (0.7–8.0 $GtCO_2$-eq yr^{-1}) (*high confidence*) had the highest potential, followed by reduced food loss and waste (0.8–4.5 $GtCO_2$-eq yr^{-1}) (*high confidence*). Measures with greatest potential for CDR were afforestation/reforestation (0.5–10.1 $GtCO_2$-eq yr^{-1}) (*medium confidence*), soil carbon sequestration in croplands and grasslands (0.4–8.6 $GtCO_2$-eq yr^{-1}) (*medium confidence*) and BECCS (0.4–11.3 $GtCO_2$-eq yr^{-1}) (*medium confidence*). The SRCCL did not explore regional potential, associated feasibility nor provide detailed analysis of costs.

IPCC AR6. This assessment concludes the likely range of global land-based mitigation potential is approximately 8 – 14 $GtCO_2$-eq yr^{-1} between 2020-2050 with carbon prices up to USD100 tCO_2-eq^{-1}, about half of the technical potential (*medium evidence; medium agreement*). About 30-50% could be achieved < USD20 tCO_2-eq^{-1} (Table 7.3). The global economic potential estimates in this assessment are slightly higher than the AR5 range. Since AR5, there have been numerous new global assessments of sectoral land-based mitigation potential (Fuss et al. 2018; Griscom et al. 2017, 2020; Roe et al. 2019; Jia et al. 2019; Griscom et al. 2020; Roe et al. 2021) as well as IAM estimates of mitigation potential (Frank et al. 2019; Johnston and Radeloff 2019; Riahi et al. 2017; Baker et al. 2019; Popp et al. 2017; Rogelj et al. 2018a), expanding the scope of AFOLU mitigation measures included and substantially improving the robustness and spatial resolution of mitigation estimates. A recent development is an assessment of country-level technical and economic (USD100 tCO_2-eq^{-1}) mitigation potential for 20 AFOLU measures, including for demand-side and soil organic carbon sequestration in croplands and grasslands, not estimated before (Roe et al. 2021). Estimates on costs, feasibility, sustainability, benefits, and risks have also been developed for some mitigation measures, and they continue to be active areas of research. Developing more refined sustainable potentials at a country-level will be an important next step. Although most mitigation estimates still do not consider the impact of future climate change, there are some emerging studies that do (Doelman et al. 2019; Sonntag et al. 2016). Given the IPCC WG1 finding that the land sink is continuing to increase although its efficiency is decreasing with climate change, it will be critical to better understand how future climate will affect mitigation potentials, particularly from CDR measures.

Across global sectoral studies, the economic mitigation potential (up to USD100 tCO_2-eq^{-1}) of supply-side measures in AFOLU for the period 2020-2050 is 11.4 mean (5.6–19.8 full range) $GtCO_2$-eq yr^{-1}, about 50% of the technical potential of 24.2 (4.9 - 58) $GtCO_2$-eq yr^{-1} (Table 7.3). Adding 2.1 $GtCO_2$-eq yr^{-1} from demand-side measures (accounting only for diverted agricultural production to avoid double counting with land-use change effects), total land-based mitigation potential up to USD100 tCO_2-eq^{-1} is 13.6 (6.7 – 23.4) $GtCO_2$-eq yr^{-1}. This estimate aligns with the most recent regional assessment (Roe et al. 2021), which found the aggregate global mitigation potential of supply and demand-side measures to be 13.8 ± 3.1 $GtCO_2$-eq yr^{-1} up to USD100 tCO_2-eq^{-1} for the period 2020-2050. Across integrated assessment models (IAMs), the economic potential for land-based mitigation (Agriculture, LULUCF and BECCS) for USD100 tCO_2-eq^{-1} is 7.9 mean (4.1–17.3 range) $GtCO_2$-eq yr^{-1} in 2050 (Table 7.3). We add the estimate for BECCS here to provide the full land-based potential, as IAMs optimize land allocation based on costs, which displaces land-based CDR activities for BECCS. Combining both IAM and sectoral approaches, the likely range is therefore 7.9–13.6 (rounded to 8–14) $GtCO_2$-eq yr^{-1} up to USD100 tCO_2-eq^{-1} between 2020-2050. Considering both IAM and sectoral economic potential estimates, land-based mitigation could have the capacity to make the AFOLU sector net negative GHG emissions from 2036 (Figure 7.12), although there are highly variable mitigation strategies for how AFOLU potential can be deployed for achieving climate targets (Illustrative Mitigation Pathways in 7.5.5). Economic potential estimates, which reflect a public willingness to pay, may be more relevant for policy making compared with technical potentials which reflect a theoretical maximum that may not be feasible or sustainable.

Among the mitigation options, the protection, improved management, and restoration of forests and other ecosystems (wetlands, savannas and grasslands) have the largest potential to reduce emissions and/or sequester carbon at 7.3 (3.9–13.1) $GtCO_2$-eq yr^{-1} (up to USD100 tCO_2-eq^{-1}), with measures that 'protect' having the single highest total mitigation and mitigation densities (mitigation per area) in AFOLU (Table 7.3, Figure 7.11). Agriculture provides the second largest share of mitigation, with 4.1 (1.7–6.7) $GtCO_2$-eq yr^{-1} potential (up to USD100 tCO_2-eq^{-1}), from soil carbon management in croplands and grasslands, agroforestry, biochar, rice cultivation, and livestock and nutrient management Table 7.3, Figure 7.11. Demand-side measures including shifting to sustainable healthy diets, reducing food waste, and improving wood products can mitigate 2.2 (1.1 - 3.6) $GtCO_2$-eq yr^{-1} when accounting only for diverted agricultural production from diets and food waste to avoid double counting with measures in forests and other ecosystems (Table 7.3, Figure 7.11). The potential of demand-side measures increases three-fold, to 6.5 (4 – 9.5) $GtCO_2$-eq yr^{-1} when accounting for the entire value chain including land-use effects, but would overlap with other measures and is therefore not additive.

Most mitigation options are available and ready to deploy. Emissions reductions can be unlocked relatively quickly, whereas CDR need upfront investment to generate sequestration over time. The protection of natural ecosystems, carbon sequestration in agriculture, sustainable healthy diets and reduced food waste have especially high co-benefits and cost efficiency. Avoiding the conversion of carbon-rich primary peatlands, coastal wetlands and forests is particularly important as most carbon lost from those ecosystems are irrecoverable through restoration by the 2050 timeline of achieving net zero carbon emissions (Goldstein et al. 2020). Sustainable intensification, shifting diets, reducing food waste could enhance efficiencies and reduce agricultural land needs, and are therefore critical for enabling supply-side measures such as reduced deforestation, restoration, as well as reducing N_2O and CH_4 emissions from agricultural production - as seen in the Illustrative Mitigation Pathway IMP-SP (Section 7.5.6). Although agriculture measures that reduce non-CO_2, particularly of CH_4, are important for near-term emissions reductions, they have less economic potential due to costs. Demand-side measures may be able to deliver non-CO_2 emissions reductions more cost efficiently.

Regionally, economic mitigation potential up to USD100 tCO_2-eq^{-1} is estimated to be greatest in tropical countries in Asia and developing Pacific (34%), Latin America and the Caribbean (24%), and Africa and the Middle East (18%) because of the large potential from reducing deforestation and sequestering carbon in forests and agriculture (Figure 7.11). However, there is also considerable potential in Developed Countries (18%) and more modest potential in Eastern Europe and West-Central Asia (5%). These results are in line with the IAM regional mitigation potentials (Figure 7.11). The protection of forests and other ecosystems is the dominant source of mitigation potential in tropical regions, whereas carbon sequestration in agricultural land and demand-side measures are important in Developed Countries and Asia and developing Pacific. The restoration and management of forests and other ecosystems is more geographically distributed, with all regions having significant potential. Regions with large livestock herds (Developed Countries, Latin America) and rice paddy fields (Asia and developing Pacific) have potential to reduce CH_4. As expected, the highest total potential is associated with countries and regions with large land areas, however when considering mitigation density (total potential per hectare), many smaller countries, particularly those with wetlands have disproportionately high levels of mitigation for their size (Roe et al. 2021). As global commodity markets connect regions, AFOLU measures may create synergies and trade-offs across the world, which could make national demand-side measures for example, important in mitigating supply-side emissions elsewhere (Kallio & Solberg 2018).

Although economic potentials provide more realistic, near-term climate mitigation compared to technical potentials, they still do not account for feasibility barriers and enabling conditions that vary by region and country. For example, according to most models, including IAMs, avoided deforestation is the cheapest land-based mitigation option (Table 7.3, Sections 7.5.3 and 7.5.4), however implementing interventions aimed at reducing deforestation (including REDD+) often have higher transaction and implementation costs than expected due to various barriers and enabling conditions (Luttrell et al. 2018; Section 7.6). The feasibility of implementing AFOLU mitigation measures, including those with multiple co-benefits, depends on varying economic, technological, institutional, socio-cultural, environmental and geophysical barriers (*high confidence*) (Smith et al. 2019a). The section for each individual mitigation measure provides an overview of co-benefits and risks associated with the measure and Section 7.6.6 outlines key enabling factors and barriers for implementation.

Table 7.3 Estimated annual mitigation potential ($GtCO_2$-eq yr^{-1}) in 2020-2050 of AFOLU mitigation options by carbon price. Estimates reflect sectoral studies based on a comprehensive literature review updating data from (Roe et al. 2019) and integrated assessment models using the IPCC AR6 database (Section 7.5). Values represent the mean, and full range of potential. Sectoral mitigation estimates are averaged for the years 2020-2050 to capture a wider range of literature, and the IAM estimates are given for 2050 as many model assumptions delay most land-based mitigation to mid-century. The sectoral potentials are the sum of global estimates for the individual measures listed for each option. IAM potentials are given for mitigation options with available data; e.g., net land-use CO_2 for total forests & other ecosystems, and land sequestration from A/R, but not reduced deforestation (protect). Sectoral estimates predominantly use GWP_{100} IPCC AR5 values (CH_4 = 28, N_2O = 265), although some use GWP_{100} IPCC AR4 values (CH_4 = 25, N_2O = 298); and the IAMs use GWP_{100} IPCC AR6 values (CH_4 =

27, N_2O = 273). The sectoral and IAM estimates reflected here do not account for the substitution effects of avoiding fossil fuel emissions nor emissions from other more energy intensive resources/materials. For example, BECCS estimates only consider the carbon dioxide removal (CDR) via geological storage component and not potential mitigation derived from the displacement of fossil fuel use in the energy sector. Mitigation potential from substitution effects are included in the other sectoral chapters like energy, transport, buildings and industry. The total AFOLU sectoral estimate aggregates potential from agriculture, forests & other ecosystems, and diverted agricultural production from avoided food waste and diet shifts (excluding land-use impacts to avoid double counting). Because of potential overlaps between measures, sectoral values from BECCS and the full value chain potential from demand-side measures are not summed with AFOLU. IAMs account for land competition and resource optimization and can therefore sum across all available categories to derive the total AFOLU potential. Key: ND = no data; Sectoral = as assessed by sectoral literature review; IAM = as assessed by integrated assessment models; EJ = ExaJoule primary energy.

Mitigation option	Estimate type	< USD20 tCO_2-eq^{-1}	< USD50 tCO_2-eq^{-1}	< USD100 tCO_2-eq^{-1}	Technical
Agriculture total	Sectoral	0.9 (0.5 - 1.4)	1.6 (1 – 2.4)	4.1 (1.7 - 6.7)	11.2 (1.6 - 28.5)
	IAM	0.9 (0 - 3.1)	1.3 (0 - 3.2)	1.8 (0.7 - 3.3)	ND
Agriculture - Carbon sequestration (soil carbon management in croplands and grasslands, agroforestry, and biochar)	Sectoral	0.5 (0.4 - 0.6)	1.2 (0.9 - 1.6)	3.4 (1.4 - 5.5)	9.5 (1.1 - 25.3)
	IAM	ND	ND	ND	ND
Agriculture - Reduce CH4 and N2O emissions (improve enteric fermentation, manure management, nutrient management, and rice cultivation)	Sectoral	0.4 (0.1 - 0.8)	0.4 (0.1 - 0.8)	0.6 (0.3 - 1.3)	1.7 (0.5 - 3.2)
	IAM	0.9 (0 - 3.1)	1.3 (0 - 3.2)	1.8 (0.7 - 3.3)	ND
Forests & other ecosystems total	Sectoral	2.9 (2.2 - 3.5)	3.1 (1.4 - 5.1)	7.3 (3.9 - 13.1)	13 (5 - 29.5)
	IAM	2.4 (0 - 10.5)	3.3 (0 - 9.9)	4.2 (0 - 12.1)	ND
Forests & other ecosystems - Protect (reduce deforestation, loss and degradation of peatlands, coastal wetlands, and grasslands)	Sectoral	2.3 (1.7 - 2.9)	2.4 (1.2 - 3.6)	4.0 (2.5 - 7.4)	6.2 (2.8 - 14.4)
	IAM	ND	ND	ND	ND
Forests & other ecosystems - Restore (afforestation, reforestation, peatland restoration, coastal wetland restoration)	Sectoral	0.15	0.7 (0.2 - 1.5)	2.1 (0.8 - 3.8)	5 (1.1 - 12.3)
	IAM (A/R)	0.6 (0.2 - 6.5)	0.6 (0.01 - 8.3)	0.7 (0.07 - 6.8)	ND
Forests & other ecosystems - Manage (improve forest management, fire management)	Sectoral	0.4 (0.3 - 0.4)	ND	1.2 (0.6 - 1.9)	1.8 (1.1 - 2.8)
	IAM	ND	ND	ND	ND
Demand-side measures (shift to sustainable healthy diets, reduce food waste, and enhanced and improved use of wood products) ** for all three only the direct avoided emissions; land use effects are in measures above*	Sectoral	ND	ND	*2.2 (1.1 - 3.6)**	*4.2 (2.2 - 7.1)**
	IAM	ND	ND	ND	ND
	Sectoral	ND	ND	1.6 (0.5 - 3.5)	5.9 (0.5 - 11.3)

BECCS (only the CDR component, i.e the geological storage. Substitution effects are accounted in other sectoral chapters: energy, transport)	IAM	0.08 (0 - 0.7)	0.5 (0 - 6)	1.8 (0.2 - 9.9)	ND
Bioenergy from residues	Sectoral	ND	ND	ND	Up to 57 EJ yr^{-1}
TOTAL AFOLU (agriculture, forests & other ecosystems, diverted ag production from demand-side)	Sectoral	3.8 (2.7 - 4.9)	4.3 (2.3 - 6.7)	13.6 (6.7 - 23.4)	28.4 (8.8 - 65.1)
TOTAL AFOLU (agriculture, forests & other ecosystems, BECCS)	IAM	3.4 (0 - 14.6)	5.3 (0.6 - 19.4)	7.9 (4.1 - 17.3)	ND

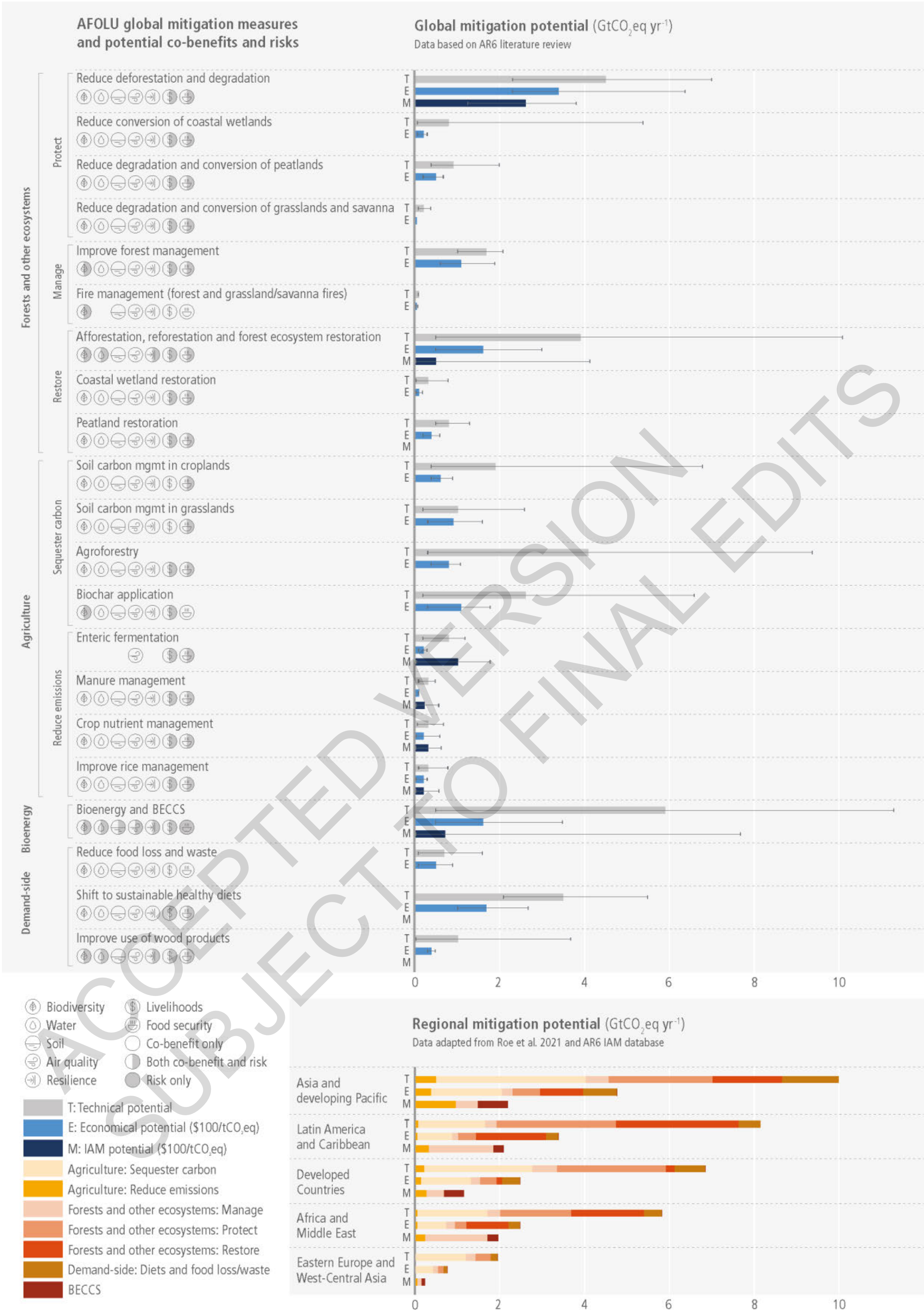


Figure 7.11 Global and regional mitigation potential ($GtCO_2$-eq yr^{-1}) in 2020–2050 for 20 land-based measures. (a) Global estimates represent the mean (bar) and full range (error bars) of the economic

potential (up to USD100 tCO_2-eq^{-1}) based on a comprehensive literature review of sectoral studies (references are outlined in the sub-section for each measure in 7.4.2–7.4.5). Potential co-benefits and trade-offs for each of the 20 measures are summarized in icons. (b) Regional estimates illustrate the mean technical (T) and economic (E) (up to USD100 tCO_2-eq^{-1}) sectoral potential based on data from (Roe et al. 2021). IAM economic potential (M) (USD100 tCO_2-eq^{-1}) data is from the IPCC AR6 database.

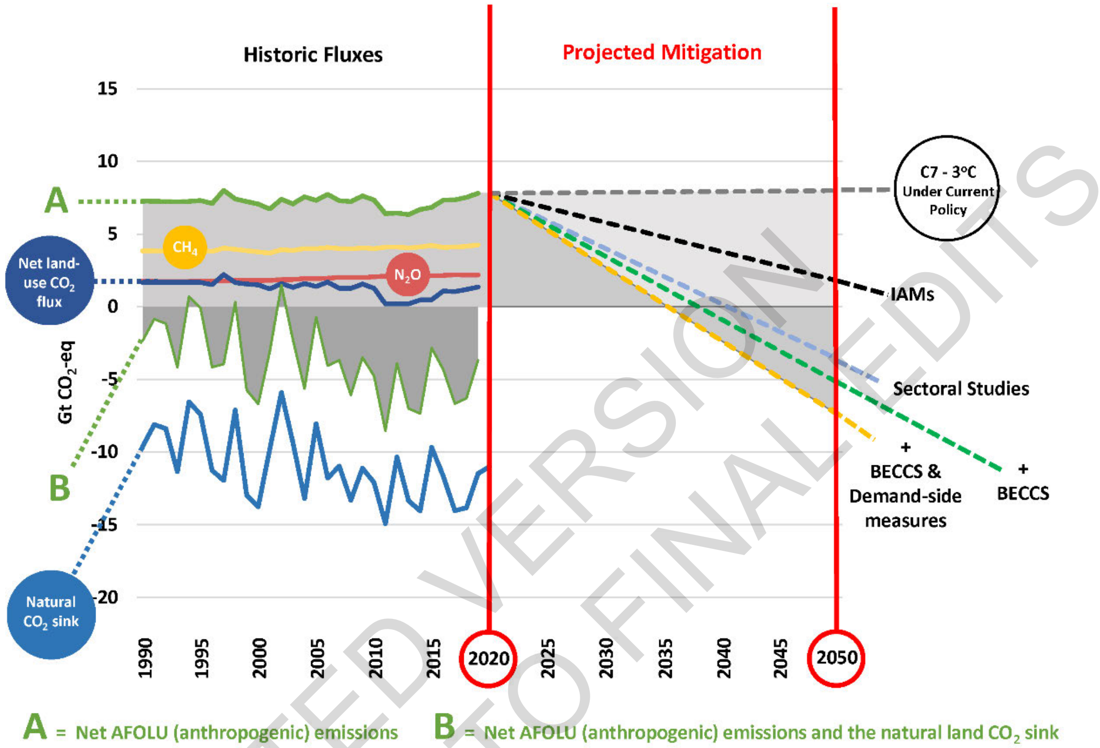


Figure 7.12 Historic land sector GHG flux estimates and illustrative AFOLU mitigation pathways to 2050, based on data presented in Sections 7.2, 7.4 and 7.5. Historic trends consider both (A) anthropogenic (AFOLU) GHG fluxes ($GtCO_2$-eq yr^{-1}) according to FAOSTAT (FAO 2021a; 2021b) and (B) the estimated natural land CO_2 sink according to (Friedlingstein et al. 2020). Note that for the anthropogenic net land CO_2 flux component, several approaches and methods are described within the literature (Section 7.2.2) with a wide range in estimates. For clarity, only one dataset (FAOSTAT) is illustrated here. It is not intended to indicate preference for one particular method over others. Historic flux trends are illustrated to 2019, the latest year for which data is available. Projected economic mitigation potential (at costs of up to USD100 tCO_2-eq^{-1}) includes estimates from IAMs and sectoral studies (Table 7.3). The sectoral estimates are disaggregated into agriculture + forests & other ecosystems, + demand-side measures (only accounting for diverted agricultural production to avoid double counting), and + BECCS (illustrating that there may be additional potential, with the caveat that there is likely overlap with other measures). Projected mitigation assumes adoption of measures to achieve increasing, linear mitigation, reaching average annual potential in 2050, although this does not reflect deployment rates for most measures. For illustrative purposes, a pathway to projected emissions in 2050 according to a scenario of current policy (C7 - Above 3.0ºC - Model: GCAM 5.3) is additionally included for reference.

7.4.2. Forests and other ecosystems

7.4.2.1. Reduce deforestation and degradation

Activities, co-benefits, risks and implementation opportunities and barriers. Reducing deforestation and forest degradation conserves existing carbon pools in forest vegetation and soil by avoiding tree cover loss and disturbance. Protecting forests involves controlling the drivers of deforestation (such as commercial and subsistence agriculture, mining, urban expansion) and forest degradation (such as overharvesting including fuelwood collection, poor harvesting practices, overgrazing, pest outbreaks, and extreme wildfires), as well as by establishing well designed, managed and funded protected areas (Barber et al. 2020), improving law enforcement, forest governance and land tenure, supporting community forest management and introducing forest certification (Smith et al. 2019b). Reducing deforestation provides numerous and substantial co-benefits, preserving biodiversity and ecosystem services (e.g. air and water filtration, water cycling, nutrient cycling) more effectively and at lower costs than afforestation/reforestation (Jia et al. 2019). Potential adverse side effects of these conservation measures include reducing the potential for agriculture land expansion, restricting the rights and access of local people to forest resources, or increasing the dependence of local people to insecure external funding. Barriers to implementation include unclear land tenure, weak environmental governance, insufficient funds, and increasing pressures associated to agriculture conversion, resource exploitation and infrastructure development (Sections 7.3 and 7.6).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Reducing deforestation and forest degradation represents one of the most effective options for climate change mitigation, with technical potential estimated at 0.4–5.8 $GtCO_2$ yr^{-1} by 2050 (*high confidence*) (SRCCL, Chapters 2 and 4, and Table 6.14). The higher technical estimate represents a complete halting of land use conversion in forests and peatland forests (i.e., assuming recent rates of carbon loss are saved each year) and includes vegetation and soil carbon pools. Ranges of economic potentials for forestry ranged in AR5 from 0.01–1.45 $GtCO_2$ yr^{-1} for USD20 tCO_2^{-1} to 0.2–13.8 $GtCO_2$ yr^{-1} for USD100 tCO_2^{-1} by 2030 with reduced deforestation dominating the forestry mitigation potential LAM and MAF, but very little potential in OECD-1990 and EIT (IPCC AR5).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since the SRCCL, several studies have provided updated and convergent estimates of economic mitigation potentials by region (Busch et al. 2019; Griscom et al. 2020; Austin et al. 2020; Roe et al. 2021). Tropical forests and /savannas in Latin America provide the largest share of mitigation potential (3.9 $GtCO_2$ yr^{-1} technical, 2.5 $GtCO_2$ yr^{-1} at USD100 tCO_2^{-1}) followed by Southeast Asia (2.2 $GtCO_2$ yr^{-1} technical, 1.5 $GtCO_2$ yr^{-1} at USD100 tCO_2^{-1}) and Africa (2.2 $GtCO_2$ yr^{-1} technical, 1.2 $GtCO_2$ yr^{-1} at USD100 tCO_2^{-1}) (Roe et al. 2021). Tropical forests continue to account for the highest rates of deforestation and associated GHG emissions. While deforestation shows signs of decreasing in several countries, in others, it continues at a high rate or is increasing (Turubanova et al. 2018). Between 2010-2020, the rate of net forest loss was 4.7 Mha yr^{-1} with Africa and South America presenting the largest shares (3.9 Mha and 2.6 Mha, respectively) (FAO 2020a).

A major uncertainty in all studies on avoided deforestation potential is their reliance on future reference levels that vary across studies and approaches. If food demand increases in the future, for example, the area of land deforested will likely increase, suggesting more technical potential for avoiding deforestation. Transboundary leakage due to market adjustments could also increase costs or reduce effectiveness of avoiding deforestation (e.g., Ingalls et al. 2018; Gingrich et al. 2019). Regarding forest regrowth, there are uncertainties about the time for the secondary forest carbon saturation (Zhu et al. 2018; Houghton and Nassikas 2017). Permanence of avoided deforestation may also be a concern due to the impacts of climate change and disturbance of other biogeochemical cycles on the world's forests that can result in future potential changes in terrestrial ecosystem productivity, climate-driven vegetation migration, wildfires, forest regrowth and carbon dynamics (Ballantyne et al. 2012; Kim et al. 2017b; Lovejoy and Nobre 2018; Aragão et al. 2018).

Critical assessment and conclusion. Based on studies since AR5, the technical mitigation potential for reducing deforestation and degradation is significant, providing 4.5 (2.3 - 7) $GtCO_2$ yr^{-1} globally by 2050, of which 3.4 (2.3 – 6.4) $GtCO_2$ yr^{-1} is available at below USD100 tCO_2^{-1} (*medium confidence)* (Figure 7.11). Over the last decade, hundreds of subnational initiatives that aim to reduce deforestation related emissions have been implemented across the tropics (Section 7.6). Reduced deforestation is a significant piece of the NDCs in the Paris Agreement (Seddon et al. 2020) and keeping the temperature below 1.5°C (Crusius 2020). Conservation of forests provides multiple co-benefits linked to ecosystem services, biodiversity and sustainable development (Section 7.6.). Still, ensuring good governance, accountability (e.g. enhanced monitoring and verification capacity; Bos 2020), and the rule of law are crucial for implementing forest-based mitigation options. In many countries with the highest deforestation rates, insecure land rights often are significant barriers for forest-based mitigation options (Gren and Zeleke 2016; Essl et al. 2018).

7.4.2.2. Afforestation, reforestation and forest ecosystem restoration

Activities, co-benefits, risks and implementation opportunities and barriers. Afforestation and reforestation (A/R) are activities that convert land to forest, where reforestation is on land that has previously contained forests, while afforestation is on land that historically has not been forested (Box 7.2). Forest restoration refers to a form of reforestation that gives more priority to ecological integrity as well, even though it can still be a managed forest. Depending on the location, scale, and choice and management of tree species, A/R activities have a wide variety of co-benefits and trade-offs. Well-planned, sustainable reforestation and forest restoration can enhance climate resilience and biodiversity, and provide a variety of ecosystem services including water regulation, microclimatic regulation, soil erosion protection, as well as renewable resources, income and livelihoods (Ellison et al. 2017; Locatelli et al. 2015; Verkerk et al. 2020; Stanturf et al. 2015). Afforestation, when well planned, can help address land degradation and desertification by reducing runoff and erosion and lead to cloud formation however, when not well planned, there are localised trade-offs such as reduced water yield or biodiversity (Teuling et al. 2017; Ellison et al. 2017) . The use of non-native species and monocultures may have adverse impacts on ecosystem structure and function, and water availability, particularly in dry regions (Ellison et al. 2017). A/R activities may change the surface albedo and evapotranspiration regimes, producing net cooling in the tropical and subtropical latitudes for local and global climate and net warming at high latitudes (Section 7.4.2). Very large-scale implementation of A/R may negatively affect food security since an increase in global forest area can increase food prices through land competition (Kreidenweis et al. 2016).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. AR5 did not provide a new specification of A/R potential, but referred to AR4 mostly for forestry measures (Nabuurs et al. 2007). AR5 did view the feasible A/R potential from a diets change scenario that released land for reforestation and bioenergy crops. AR 5 provided top-down estimates of costs and potentials for forestry mitigation options - including reduced deforestation, forest management, afforestation, and agroforestry, estimated to contribute between 1.27 and 4.23 $GtCO_2$ yr^{-1} of economically viable abatement in 2030 at carbon prices up to USD100/t CO_2-eq (Smith et al. 2014).

The SRCCL remained with a reported wide range of mitigation potential for A/R of 0.5–10.1 $GtCO_2$ yr^{-1} by 2050 (*medium confidence*) (SRCCL Chapters 2 and 6; Roe et al. 2019; Fuss et al. 2018; Griscom et al. 2017; Hawken 2017; Kreidenweis et al. 2016). The higher estimate represents a technical potential of reforesting all areas where forests are the native cover type (reforestation), constrained by food security and biodiversity considerations, considering above and below-ground carbon pools and implementation on a rather theoretical maximum of 678 Mha of land (Roe et al. 2019; Griscom et al. 2017). The lower estimates represent the minimum range from an Earth System Model and a sustainable global CDR potential (Fuss et al. 2018). Climate change will affect the mitigation potential of reforestation due to impacts in forest growth and composition, as well as changes in disturbances including fire. However, none of the mitigation estimates included in the SRCCL account for climate impacts.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since SRCCL, additional studies have been published on A/R mitigation potential by Bastin et al. (2019), Lewis et al. (2019), (Doelman et al. 2019), (Favero et al. 2020) and (Austin et al. 2020). These studies are within the range reported in the SRCCL stretching the potentials at the higher range. The rising public interest in nature-based solutions, along with high profile initiatives being launched (UN Decade on Restoration announced in 2019, the Bonn challenge on 150 million ha of restored forest in 2020 and e.g. the trillion-tree campaign launched by the World Economic Forum in 2020), has prompted intense discussions on the scale, effectiveness, and pitfalls of A/R and tree planting for climate mitigation (Anderegg et al. 2020; Bond et al. 2019; Heilmayr et al. 2020; Holl and Brancalion 2020; Luyssaert et al. 2018). The sometimes sole attention on afforestation and reforestation suggesting it may solve the climate problem to large extent in combination with the very high estimates of potentials have led to polarisation in the debate, again resulting in a push back to nature restoration only (Lewis et al. 2019). Our assessment based on most recent literature produced regional economic mitigation potential at USD100 tCO_2^{-1} estimate of 100-400 $MtCO_2$ yr^{-1} in Africa, 210-266 $MtCO_2$ yr^{-1} in Asia and developing Pacific, 291 $MtCO_2$-eq yr^{-1} in Developed countries (87% in North America), 30 $MtCO_2$-eq yr^{-1} in Eastern Europe and West-Central Asia, and 345-898 $MtCO_2$-eq yr^{-1} in Latin America and Caribbean (Roe et al. 2021), which totals to about 1200 $MtCO_2$ yr^{-1}, leaning to the lower range of the potentials in earlier IPCC reports. A recent global assessment of the aggregate costs for afforestation and reforestation suggests that at USD100 tCO_2^{-1}, 1.6 $GtCO_2$ yr^{-1} could be sequestered globally for an annual cost of USD130 billion (Austin et al. 2020). Sectoral studies that are able to deal with local circumstances and limits estimate A/R potentials at 20 $MtCO_2$ yr^{-1} in Russia (Eastern Europe and West-Central Asia) (Romanovskaya et al. 2020) and 64 $MtCO_2$ yr^{-1} in Europe (Nabuurs et al. 2017). (Domke et al. 2020) estimated for the USA an additional 20% sequestration rate from tree planting to achieve full stocking capacity of all understocked productive forestland, in total reaching 187 $MtCO_2$ yr^{-1} sequestration. A new study on costs in the USA estimates 72-91 $MtCO_2$ yr^{-1} could be sequestered between now and 2050 for USD100/t CO_2 (Wade et al. 2019). The tropical and subtropical latitudes are the most effective for forest restoration in terms of carbon sequestration because of the rapid growth and lower albedo of the land surface compared with high latitudes (Lewis et al. 2019).. Costs may be higher if albedo is considered in North America, Russia, and Africa (Favero et al. 2017). In addition, a wide variety of sequestration rates have been collected and published in e.g. IPCC Good Practice Guidance for the AFOLU sector (IPCC 2006).

Critical assessment and conclusion. There is *medium confidence* that the global technical mitigation potential of afforestation and reforestation activities by 2050 is 3.9 (0.5–10.1) $GtCO_2$ yr^{-1}, and the economic mitigation potential (< USD100 tCO_2^{-1}) is 1.6 (0.5 – 3.0) $GtCO_2$ yr^{-1} (requiring about 200 Mha). Per hectare a long (about 100 year) sustained effect of 5-10 $t(CO_2)$ ha^{-1} yr^{-1} is realistic with ranges between 1-20 $t(CO_2)$ ha^{-1} yr^{-1}. Not all sectoral studies rely on economic models that account for leakage (Murray et al. 2004; Sohngen and Brown 2004), suggesting that technical potential may be overestimated.

7.4.2.3. Improved forest management

Activities, co-benefits, risks and implementation opportunities and barriers.