CHAPTER 7

Mitigation measures in energy systems

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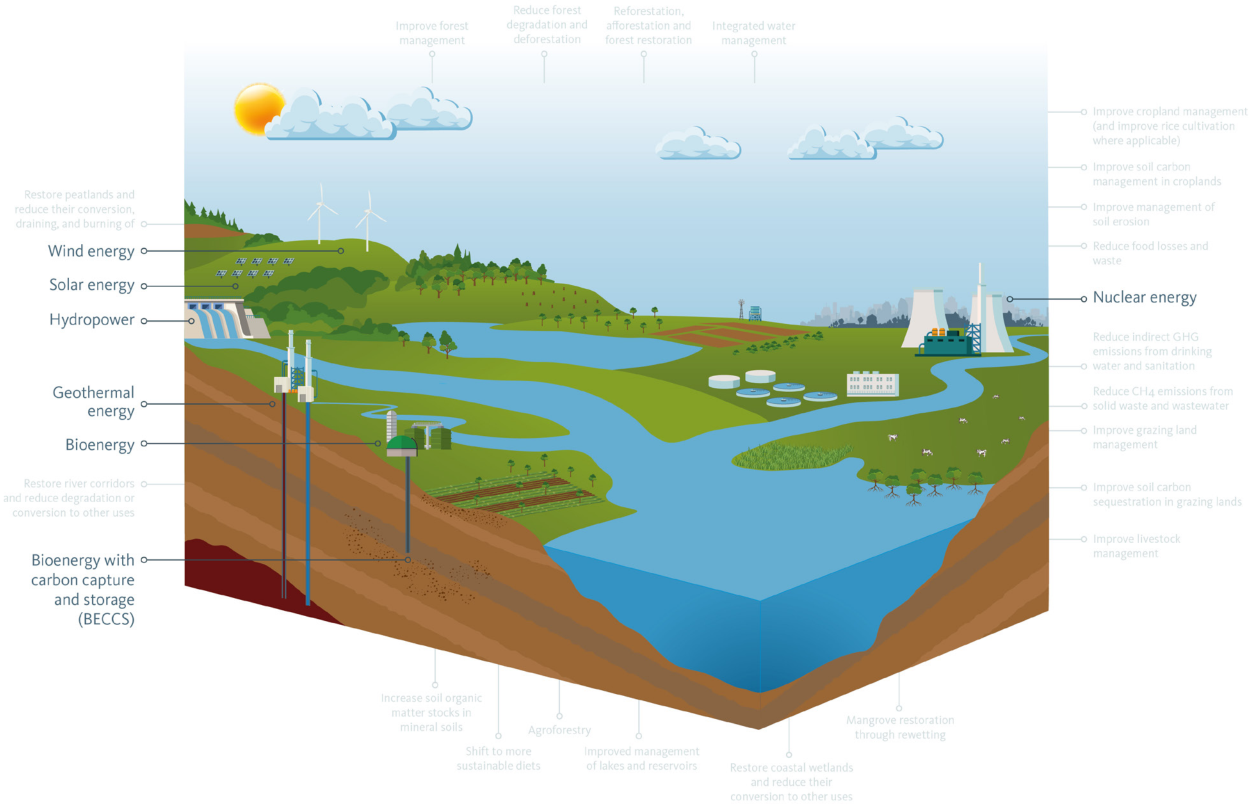

Figure 7.0. Mitigation measures in energy systems. Source: SIWI.

Highlights

- Water is a significant consideration for all energy production except possibly wind power and solar PV. Bioenergy, hydropower and thermal energy generation from solar, geothermal, and nuclear power are low-emission energy sources with substantial water requirements. The benefits provided by these options must be weighed against potential water risks and impacts on freshwater ecosystems.
- Low-emission energy transition plans must include analysis of projected demands, availability, and impacts on water as well as potential risks to water availability caused by climate change. Effective water management to buffer against the impacts of climate change is needed to protect energy infrastructure and ensure the reliable supply of electricity and energy sources.
- Transitions toward low-emission energy can reduce pressure on water, but this will depend on the future mix and management of energy sources. The transition to renewable energies can create opportunities to reduce pressure and impacts on water resources from the energy sector, due primarily to lower water demands from solar photovoltaic (PV) and wind generation compared with fossil fuels.
- As some of these transitions can potentially increase pressure on water resources, related risks must be considered in energy planning. Low-emission scenarios with high demand for negative emissions imply an increase in water consumption, particularly for bioenergy, with large ranges in potential water requirements. Low emission energy scenarios often lack quantification of impacts on water quality and ecosystems, which must be incorporated in national, local, and regional planning.
- Mitigation strategies including bioenergy must consider their potential impacts on and demand for water sources. How much, where, which type, and how to produce bioenergy are critical questions that potentially have the largest impact on the global water cycle. Sustainable water management in bioenergy with carbon capture can in certain contexts provide both energy and climate mitigation benefits.
- Expansion of solar and wind power and efficiency improvements account for meeting as much as 50 per cent of energy demand by 2050 in many scenarios to meet climate targets. If not reached, there is likely to be greater demand and pressure placed on water resources from all other alternatives. To enable this expansion, strategies are also needed to mitigate potential water risks for energy storage solutions, including pumped hydropower as well as mining for minerals such as cobalt, copper, lithium, and rare earth materials.

7.1 Introduction

Global warming cannot be limited to well below 2°C (above pre-industrial levels) without rapid and deep reductions in greenhouse gas (GHG) emissions from energy systems. The International Energy Agency (IEA 2022) estimates that 36.3 gigatonnes (Gt) of CO_2 emissions resulted from energy combustion and industrial processes in 2021, which was an increase of 6% over the previous year. This is the largest source of global emissions, accounting for nearly three quarters, coming primarily from the use of fossil fuel energy sources (IEA 2018). In 2020, about 80 per cent of total energy supply was derived from oil, coal, and natural gas (IEA 2020a). The transition to renewable, cleaner energy sources is central to all climate mitigation plans and pathways towards achievement of the Paris Agreement targets. In the IPCC (2022) modelled pathways to reach global net zero by 2050 – a majority of GHG reductions (ranging between 54 – 90 per cent) are projected to be achieved through shifts to low-emission energy supply and curbing energy demand. Despite the recent growth in renewable energy deployment and low-carbon energy technologies, emissions from the energy sector need to be reduced further. An additional 12 Gt of CO_2 emissions need to be abated by 2030 to get the world on track for reaching net zero energy emissions targets, and this needs to be accompanied by reductions of almost 90 million tons (Mt) in methane emissions from fossil

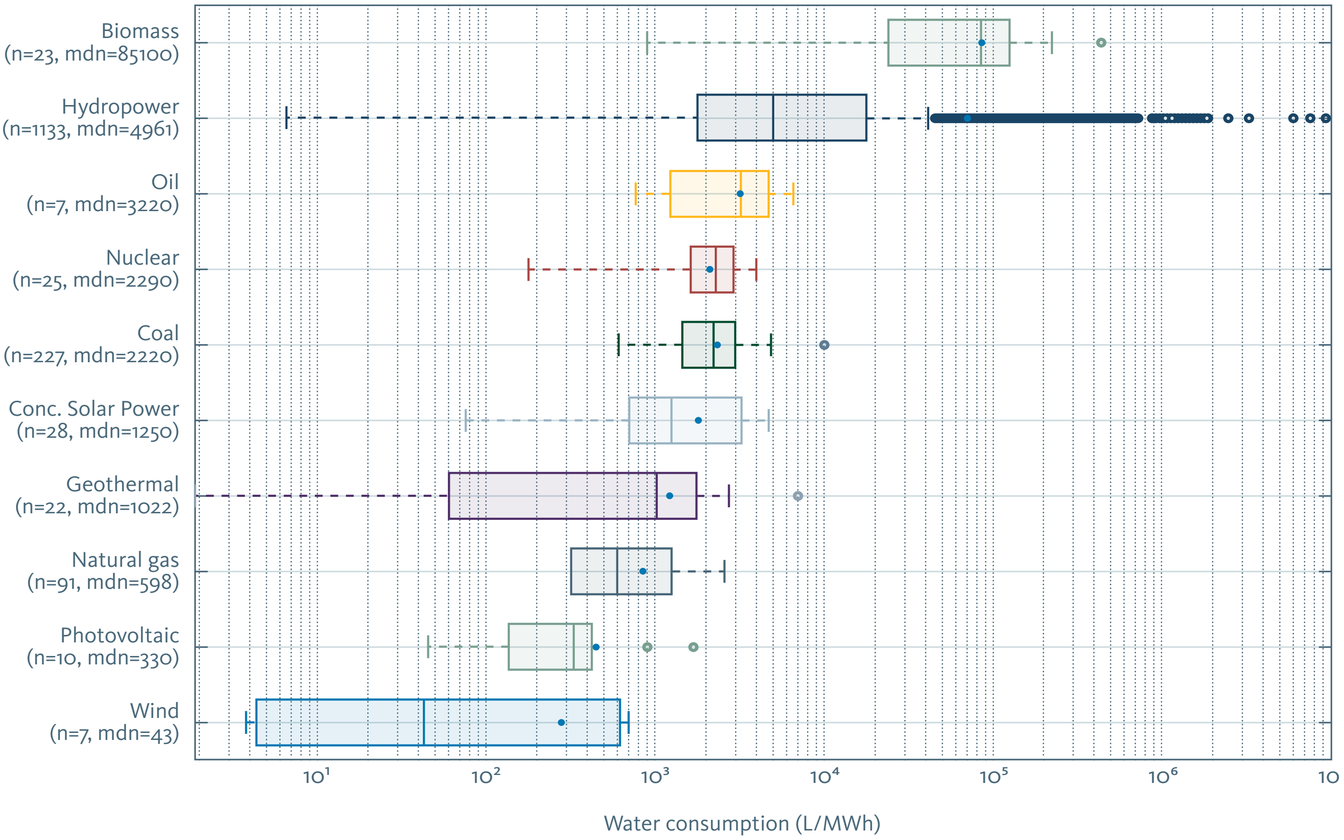

Figure 7.1. Range and median estimate of water use for electricity production by type measured in litres of water per megawatt hour of electricity produced. Source: Jin et al. (2019).

fuel operations (equivalent to another 2.7 Gt of CO_2 emissions) (IEA 2021f). This would be 25 per cent below the International Energy Agency (IEA) Sustainable Development Scenario targets in previously estimated Intergovernmental Panel on Climate Change (IPCC) pathways (Rogelj et al. 2018), and drastically divergent from current stated policies and commitments, which set a track for a slight increase in emissions to 36 Gt by 2030 (IEA 2021f).

In all energy investments, planning, and operations, the water required during the production process and the impacts of the energy production process on water resources and ecosystems need to be considered. In some parts of the energy mix, water is a central component generating, storing, or transferring such energy as hydropower and geothermal power or some hydrogen storage technologies. The requirements and impacts on water vary between energy carriers and depend on the way in which each energy carrier is being produced (Jin et al. 2019, Figure 7.1).

This chapter provides an overview of the role of freshwater in energy production of non-fossil-fuel energy sources. Each of the low-emission energy types (hydropower, bioenergy, geothermal, nuclear, solar, and wind) are presented as a mitigation measure and described in individual sections. This report reviews current uses of each energy type and projections from scenarios provided by IEA (IEA 2021f), the International Renewable Energy Agency (IRENA) (IRENA 2020), and IPCC (Rogelj et al. 2018) that are in line with limiting global warming to 1.5°C (above pre-industrial levels) and achieving net zero emissions. Under the IEA pathway to net zero emissions by 2050, the energy sources covered in this chapter will need to provide 90 per cent of electricity and 80 per cent of total energy supply, as coal and oil power plants (without carbon capture and storage [CCS]) will be phased out (IEA 2021f). The mitigation potential for each energy technology is discussed in terms of both the estimated emissions of GHG per unit of energy/electricity produced and estimates of reductions in emissions provided compared to fossil alternatives. Figure 7.2 provides a summary of estimates from IPCC (2022) showing estimated mitigation potential of each energy option assessed in this chapter. Besides quantitative estimates on water demand for each mitigation measure, this assessment covers implications for water governance and management, as well as co-benefits and trade-offs.

Many options available now in all sectors are estimated to offer substantial potential to reduce net emissions by 2030. Relative potentials and costs will vary across countries and in the longer term compared to 2030.

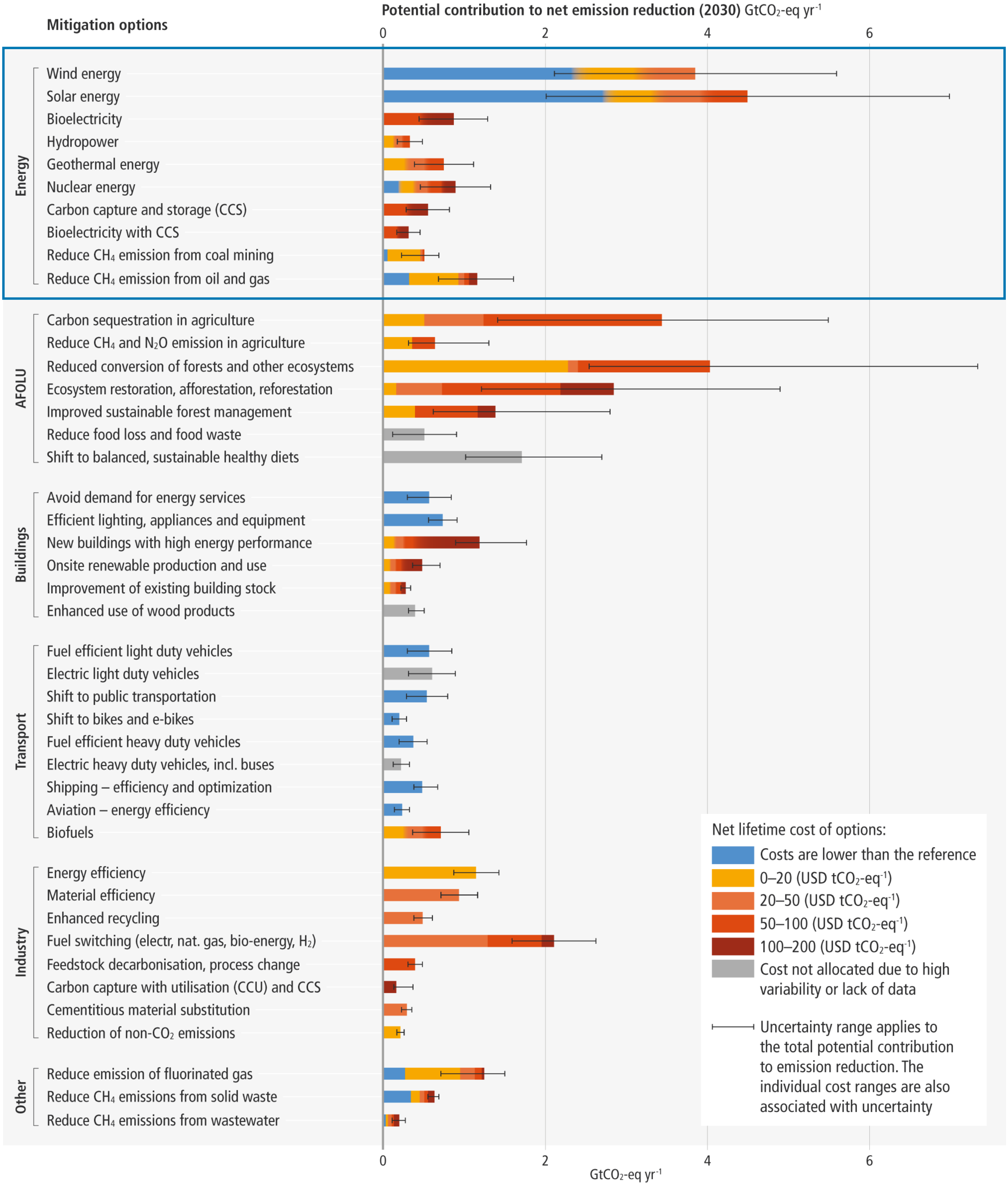

Figure 7.2. Mitigation measures within the energy sector (top box) and their mitigation potential to reduce net emissions by 2030. Source: IPCC Sixth Assessment Report, https://www.ipcc.ch/report/ar6/wg3/figures/summary-for-policymakers/figure-spm-7/.

Nuclear power is included as a mitigation measure as it is present in most scenario pathways for climate mitigation to achieve the Paris Agreement targets and has significant implications on water resources. Natural gas and coal power with CCS, however, are not classified as mitigation measures because they still have a significant emission factor (Jacobson 2020). As these energy sources remain part of most climate mitigation planning at present, the implications of CCS on mitigation and water are reviewed in brief in Box 7.1.

Measures to improve energy efficiency and reduce demand are also critical. IEA (IEA 2020a) projects that for scenarios depending upon technologies alone, half of emission reductions would depend on solutions that are not yet commercially viable. Demand management and efficiency are likewise needed to reduce overall pressure on water sources for energy production but are not covered here as specific mitigation measures. This is discussed further in Chapter 8 as a cross-cutting type of measure that also applies to water systems (Chapter 4) and land systems (Chapter 6). Green hydrogen, energy storage, and battery technologies are also discussed separately in Box 7.4, as these are critical issues and potential enablers for renewable energy transitions but are not classified as direct mitigation measures. Following a review of each energy type, the chapter concludes with an outlook of key issues to be addressed for future water, climate, and energy security.

Box 7.1. Non-renewable energy sources and water: Natural gas and coal power with CCS

In 2018, coal (38 per cent) and natural gas (23 per cent) accounted for over 60 per cent of electricity generation (IEA 2020b). These are expected to reduce to less than half of total electricity production in 2022, showing progress in the acceleration of renewable sources on the market (IEA 2021c). Coal power generation requires large volumes of water, primarily for cooling in thermal plants. Natural gas, while emitting somewhat less CO_2 than oil and coal, has a much higher emissions factor than renewable alternatives. Moreover, leakages from natural gas plants have been found to directly emit large quantities of methane, a very potent GHG, posing great climate risks (Alvarez et al. 2018). Natural gas abstraction produces large volumes of contaminated water. Hydraulic fracturing, which involves pumping liquids at high pressure to fracture rock surfaces to release natural gas, is both water intensive and poses risks for contamination of hazardous chemicals if generated wastewater is not properly treated and disposed of. Natural gas is also used in thermal electric power plants, which can also withdraw and consume significant volumes of water. As is the case for all thermal electric plants, the requirement for water, both withdrawn and consumed, depends on the type of turbine and cooling system used (see Box 7.5).

The addition of carbon capture processes to coal and natural gas power generation is likely to be part of the energy transition and will lower emissions. IPCC notes that increasing CCS for fossil and biomass carbon is a common key characteristic in most assessed energy pathways to reach the 1.5°C target (Rogelj et al. 2018). Rosa et al. (2021) estimated that the water footprint of CCS can range from roughly 1 to 575 cubic metres of water per ton of CO_2 captured, depending upon the energy source and technology used. Adding CCS to coal and natural gas plants will increase the consumption of water resources to varying degrees depending upon the capture technology used and the cooling system installed at the plant. Magneschi et al. (2017) estimated that this typically ranges between 20 and 60 per cent of water consumption for plants that use wet recirculating cooling processes. Byers et al. (2016) found ranges of increased cooling water demand for power plants adding CCS across several studies to be 44–140 per cent. This increased water demand is already viewed as a potential barrier to uptake, particularly if no additional efficiency measures are taken (Byers et al. 2016). There is also potential to add CCS to reduce industrial production emissions, for example in cement and steel production (IEA 2021c). Rosa et al (2021) found that widespread use of CCS to achieve the climate targets found in some scenarios could potentially double overall freshwater demand globally. Bioenergy with CCS (BECCS), which has the highest potential water demand, is covered in section 7.3.

Box 7.2. Measurement units for energy, electricity, fuels, and heating

Energy consumption is categorized primarily by the use of fuels for transport, buildings, industries, and power generation. Electricity and heat generation are measured in terms of joules, watts (capacity to produce a certain amount of electricity), and watt hours (provision of electricity of a certain amount over time). Energy consumption from fuels is measured in tons of oil equivalent (TOE), defined as the amount of energy released from burning one ton of crude oil. The energy requirements to produce electricity can be converted to TOE for comparison and these are used generally to measure energy supply and use. Globally, in 2018, 20 per cent of total final energy consumption was used for electricity generation from renewable sources (IEA 2020b). This was projected to rise to 27 per cent in 2021 (IEA 2021c).

7.2 Hydropower

7.2.1 Mitigation potential

Hydropower plants generate electricity by using flowing water to spin a turbine and connecting this to a generator. The main types of hydropower technology include a) run-of-the-river systems, which channel flowing water from a river through a canal or penstock; b) storage hydropower, which are larger systems that use a dam to store water in a reservoir and release water through a turbine; and c) pumped storage hydropower, which pumps water between a lower and upper reservoir and uses surplus energy at times of low demand.

Hydropower is currently the largest source of renewable electricity generation in the world and second-largest renewable energy source to bioenergy. The 2022 hydropower status report (IHA 2022) states that installed capacity for hydropower worldwide was 1360 GW and, respectively, 4250 TWh of electricity generated in 2021. Hydropower accounts for about 45 per cent of current renewable energy generation, and 16 per cent of total electricity production (IEA 2021e). Over the past five years, hydropower capacity has increased by about 2 per cent annually (IHA 2021). The International Hydropower Association (IHA) states that an additional 500 GW of installed capacity is in the pipeline today, and IEA projects an additional growth of 17 per cent over current capacity during the next decade, the majority of which will be in Africa and East Asia (IHA 2021; IEA 2021i). In some scenarios for achieving emission reduction targets in the energy sector, the expected increase is even more significant, ranging from a further 850 GW to 1,300 GW of additional installations. IEA net zero scenarios project hydropower production to double by 2050 (IEA 2021f) and the IRENA Global Renewable Outlook - Energy Transformation 2050 scenarios for a renewable energy mix required to achieve net zero emission targets for 2050 estimated a 60 per cent overall increase in hydropower and 200 per cent increase in pumped hydropower annual production over the next 30 years (IRENA 2020).

Hydropower is generally categorized as a low-emission energy technology (IHA 2021; IEA 2021i); however, there is debate as to whether the emissions from hydropower reservoirs are measured sufficiently. The GHG emissions from hydropower production differ based on the conditions surrounding the hydropower plant and reservoir, which makes it difficult to use average emission rates at project or country level (Bruckner et al. 2014; Kumar et al. 2011). (Ubierna et al. 2022) assessed global median life-cycle GHG emissions to be 23 grammes CO_2 equivalent per kilowatt hour, based on analysis of nearly 500 hydropower storage projects. Emissions from hydropower across the life cycle of plant construction and operation are influenced by a number of factors (Pfister and Nauser 2020). Emissions result when organic material settles and decomposes in the reservoir water and releases CO_2 and methane. Traditional estimates of direct emissions from hydropower may underestimate the actual emissions, as assessments can lack data or consideration for methane emissions in reservoirs, the effects of the accumulation of GHGs over time, and indirect emissions from hydropower plant construction (Ocko and Hamburg 2019). These factors can lead to a wide variance of emissions resulting from hydropower that are affected by location, design, and use of plants, and, in some cases, can negate positive mitigation impacts. There are

Table 7.1. Regional installed capacity and annual hydropower generation in 2021

REGION	INSTALLED CAPACITY (GW)	POWER GENERATION (TWh)
Africa	38	146
Asia-Pacific	523	1639
South and Central Asia	157	537
Europe	255	659
North and Central America	206	702
South America	177	658
Global	1360	4250

Source: International Hydropower Association (2022).

also indirect emissions that result from different stages across the life cycle of hydropower installations, such as construction, operation, and decommissioning of plants (Kumar et al. 2018). Improved data and measurement of emissions resulting from hydropower installations and operations are needed to enable net emission reductions (see Chapter 5).

7.2.2 Geographical distribution

Hydropower is developed and in operation in all major regions, with the largest installed capacity in East Asia and the Pacific (see table 7.1). China, Brazil, United States of America (USA), Canada and India have the highest amounts of installed national capacity. Within the next five years, the Asia-Pacific region, particularly China, is expected to see the greatest development of additional hydropower (over 65 per cent of projected growth), followed by Latin America, North America and Europe (IEA 2021i). The regions with the greatest future potential and projected growth of hydropower are East Asia and the Pacific, Africa, and South and Central Asia (IHA 2022).

7.2.3 Water dependence and impacts

The impacts and dependence of hydropower on water are direct and well known. Hydropower produces energy using water, so is entirely dependent on this resource. Large volumes of water move through hydropower systems to generate power and this power generation potential is heavily impacted by the quantity of water flowing through the system. Potential changes in the volume of water due to climate change (increasing evapotranspiration and decreasing water inflow) or withdrawals for other uses must be considered to ensure that the actual energy generation of a hydropower plant is close to the assessed installed capacity. Reservoir-based hydropower infrastructure blocks, diverts, and changes the natural flow of a river, fundamentally impacting surrounding ecosystems. This can negatively affect fish migration and breeding, with knock-on impacts on overall ecosystem health and less fish for human consumption. Reductions in water and sediment flows resulting from dams can have further impacts on downstream wildlife populations and habitats. Some water is lost through evaporation during storage and use, and this varies according to different conditions (Scherer and Pfister 2016). Jin et al. (2019) found the median level of water consumption across several studies to be 4,961 litres per megawatt hour of electricity produced. There is a need for improved data on global water use and the impacts of hydropower. While there are studies to assess water use and consumption in specific hydropower installations, there is such high variance that the impacts are difficult to project. The variation in hydropower water use estimates also stems from discrepancies in the ways that water use and consumption are defined, such as differences between accounting for gross or net evaporation, or attributions of evaporation in reservoirs between various users and causes (Larsen et al. 2019; Engström et al. 2019; Herath et al. 2011). As a result, water use and consumption for hydropower is sometimes omitted in global assessments (e.g., IEA 2018). Recent studies in China (Tian et al. 2021) and the USA (Zhao and Gao 2019) have estimated that water loss through evaporation from reservoirs is significant, reaching several hundred cubic kilometres globally each year.

7.2.4 Co-benefits and trade-offs

Hydropower plants and multi-purpose water infrastructure can provide additional co-benefits such as water storage and flood protection. Hydropower is a large industry, employing over 2 million people worldwide (IRENA 2021). Reservoir and pumped storage hydropower can be used to provide flexibility in energy systems enabling an increased share of variable renewable energies. This can enable the expanded use of solar, wind, and other clean energy sources. Hydropower can also be used as a potential energy source to develop green hydrogen fuels in the future (IHA 2021).

There can also be significant social and environmental impacts of hydropower development. Environmental issues can include negative impacts on hydrological regimes, water quality, sedimentation, biodiversity, disruptions to fish migration and spawning, and others, as described in the previous section (Kumar et al. 2011). Social impacts can include required (and sometimes forced) relocations of populations living in areas surrounding hydropower construction. While dams can in some cases support flood protection downstream, there can also be higher risks of flooding upstream in areas surrounding constructed reservoirs, as well as more devastating flood events occurring if there are dam breakages. Trade-offs between benefits provided through energy generation and environmental or social consequences downstream can also lead to tensions and challenges between riparian countries sharing a river system where the hydropower is installed (Brunner et al. 2019; Elsayed et al. 2022; Dombrowsky and Hensengerth 2018).

7.2.5 Potential implications for governance

The effective planning, design, and management of hydropower is essential. Emissions from hydropower facilities with poor siting, design, and management may be underestimated to the extent that they provide limited or even no climate mitigation benefits compared with alternatives (Ocko and Hamburg 2019). Improved estimates of potential impacts on nitrous oxide and methane emissions from existing and potential new hydropower reservoirs are needed. Assessment of potential climate impacts on hydropower across the lifecycle of construction and operations is critical and requires a thorough analysis of various models. Studies from IEA in Asia (IEA 2021b) and Latin America (IEA 2021a) project a decrease in hydropower generation potential due to climate change, and recommend building more robust climate databases and strengthening climate impact assessments. Additional actions to integrate climate resilience in early stages of hydropower projects include the creation of climate-resilient construction codes, and mandatory climate risk assessments and emergency response plans (IEA 2021b). Evaluation in advance of investment should be made to ensure that the environmental and social costs do not outweigh the potential benefits gained through the energy generated. The potential inequities of the distribution of benefits and negative impacts between groups must also be considered in this evaluation. This requires attention on several areas that need careful consideration, such as the impacts on local communities, water balance and ecosystem alterations caused by existing and new hydropower developments; the impact of climate change on hydropower generation during its operational lifetime; potential increased emissions from water bodies that result from alterations caused by hydropower installations; and effective processes in transboundary basins to ensure benefits are shared and downstream impacts accounted for. Some applications of best practice to assess and minimize environmental and social impacts can be found, including hydropower sustainability tools (IHA 2021), which include guidance on actions to take regarding resettlement, biodiversity, and downstream flow impact reductions and sediment management. Guidance materials include risk management guides and sustainability standards to rate environmental, social, and governance performance produced by IHA and the World Bank (e.g., Lyon 2020).

7.3 Bioenergy

7.3.1 Mitigation potential

Bioenergy currently accounts for about 10 per cent of total global energy supply (IEA 2021h). It is used for different purposes, such as electricity generation, transport, and heating. Aside from traditional cooking and heating with biomass, the pathways used for conversion of biomass into energy are commonly categorized as first- and second-generation bioenergy

Table. 7.2. Characteristic differences between first- and second-generation biomass feedstock.

CHARACTERISTIC	FIRST-GENERATION BIOENERGY	SECOND-GENERATION BIOENERGY
Feed stock	Sugar/starch rich fruits (e.g., sugarcane, sugar beet, maize), oil-fruits (e.g., rapeseed, sunflower, soy, oil-palm)	Lignocellulose biomass (e.g., miscanthus, switchgrass, willow, poplar, eucalyptus), biomass residues from agriculture/forestry, solid waste
Processing pathways	Fermentation, chemical conversion of oil to biodiesel	Combustion, thermo- and biochemical conversion
Target energy carrier	Bioethanol, biodiesel	Electricity/heat, hydrogen/bioethanol
Potential for carbon capture and storage	Low	High (combustion/heat/hydrogen), low for bioethanol

Source: Based on Lee and Lavoie (2013)

(Table 7.2). First-generation bioenergy refers to the production of fuels (bioethanol and biodiesel) from oil fruits (e.g., rapeseed, oil palm, sunflower) or sugar plants (e.g., sugarcane, sugar beet). Second-generation bioenergy uses biomass from plant lignocellulose, solid waste or residual biomass (from forestry or agricultural activities) that is generally converted into electricity or heat (and in some cases bioethanol). Combustion of biomass is performed in a similar way to that of coal-fired power generation (Ali and Kumar 2017).

In 2020, 7 per cent of liquid fuels for road transport came from biofuels, and over 90 per cent of those fuels came from first-generation sources, such as bioethanol and biodiesel (IEA 2021h). Currently, 330 million hectares of arable land is dedicated to the production of energy crops (IEA 2021h). Due to conflicts with food production, land, and water resources, expansion of energy crops for direct conversion to fuels is limited in most scenarios for climate mitigation (IEA 2021f; IRENA 2020). In 2018, global bioenergy production was 55.6 exajoules (EJ) (World Bioenergy Association 2020). Biofuels are the third-largest source of renewable electricity production at 637 TWh, accounting for 9 per cent of renewable electricity production and over 2 per cent of total electricity production. Two thirds of this is generated from solid biomass, with the remaining amount coming from municipal and industrial waste and biogas (World Bioenergy Association 2020). Bioenergy provides 95 per cent of renewable sources for heating and cooking, and 10 per cent of total energy for heating (IEA 2020a). In the scenarios for energy production evaluated by IPCC (Rogelj et al. 2018), global annual bioenergy production will account for 118–312 EJ in the year 2050, with average values of 200 EJ. The use of modern bioenergy is projected to grow substantially under many low-emission transition projections. The use of modern forms of solid bioenergy increases by 30–70 per cent by 2030 across IEA low-emissions and net zero emissions scenarios (IEA 2021g). Expansion of biogas for clean cooking in the IEA net zero emissions projections has the potential to serve 400 million people by 2030.

Bioenergy GHG emissions occur during land-use conversion and the harvesting, transport, processing, and conversion (through e.g., burning) of biomass. These emissions may be offset to various degrees by CO_2 absorption that takes place during crop growth (Welfle et al. 2020; US EIA 2021). The emission factor of using biomass to produce fuel, heat, or electricity can thus vary significantly. Life-cycle emissions per unit of electricity produced from biomass is currently significantly higher than for all other renewable alternatives (Rogelj et al. 2018).

7.3.2 Bioenergy with Carbon Capture and Storage

Bioenergy with Carbon Capture and Storage (BECCS) is required for low-emission bioenergy production and can potentially achieve negative emissions. BECCS is a negative emission technology that may sequester significant amounts of carbon from the atmosphere, while also using biomass to produce electricity or fuels. BECCS combines second-generation bioenergy (primarily through the production of biomass on plantations from plant lignocellulose) with the industrial combustion/fermentation and subsequent extraction and storage in geologic reservoirs of (part of) the carbon sequestered (Lenton 2010; Azar et al. 2006; Carbo et al. 2011; Caldeira et al. 2013). To avoid competition with food production, this biomass generally should not be produced on land otherwise used for primary crop production. BECCS is a relatively recently proposed approach, compared to first-generation bioethanol/biodiesel production (Laude et al. 2011), which is still under research and testing with no current large-scale deployment (Fajardy et al. 2019; Gough and Mander 2019). CCS techniques capture CO_2 from industrial processes. For BECCS this happens in the phase of biomass combustion for electricity generation or in the chemical conversion processes to biofuels. The CO_2 is compressed and pumped into geologic reservoirs with the aim to provide long-term storage (Bui et al. 2018). These CCS techniques remain at a stage of modest demonstration (Gough and Vaughan 2017) and large-scale field studies for BECCS process chains are missing (Fuss and Johnsson 2021). Electricity generation in this process is generally thought to have much higher carbon conversion efficiencies than liquid biofuel production (Lenton 2010; Fajardy et al. 2019).

7.3.3 Geographical distribution

The largest biofuel-producing regions currently include Brazil, China, India, and the USA, as well as Southeast Asia. China, Brazil, and India produce the most ethanol (8, 6 and 2 billion litres respectively), and the USA and Association of Southeast Asian Nations (ASEAN) countries produce the most biodiesel and hydro-treated vegetable oils (5 and 6 million litres respectively) (IEA 2021h). The global potential development of BECCS is determined by the availability of suitable land, water, and climate conditions (Ai et al. 2021; Bruckner et al. 2018; Stenzel et al. 2021a).

7.3.4 Water dependence and impacts

The cultivation of biomass for conversion to fuel or electricity requires substantial amounts of freshwater and land to support the plant growth. This water can come from rainfall or can be taken from rivers, lakes, reservoirs, or aquifers for irrigation. For BECCS, additional water is required to support the CCS performed at the power plant, which is estimated at roughly 450 cubic metres of water to sequester 1 ton of CO_2 (Smith et al. 2015). To maximize biomass yields, the cultivated plants should combine fast growth and robustness to the local climate. Management (e.g., use of fertilizer and irrigation water) plays a key role in both the potential development of biomass and its impact on water sources (see Box 7.3).

Soil erosion can result from land-use change, e.g., when natural forest is converted to cropland, with likely impacts on streamflow (including increased risk of floods) and groundwater recharge. Changes in vegetation

Train delivering fuel to the biomass plant at Drax power station, UK, which is currently investing in BECCS infrastructure.
Source: Shutterstock.

also affect moisture availability and recycling, not only locally but also in remote regions that are linked through the climate system (Wang-Erlandsson et al. 2017). Agrochemicals and pesticides used in biomass cultivation can cause freshwater ecotoxicity (Nordborg 2013).

Irrigation is probably needed in many areas to maximize the productivity and CO_2 sequestration capacity of the vegetation. Land constraints on the cultivation of future second-generation bioenergy for BECCS are likely to increase dependency on irrigation water (Jans et al. 2018). The potential requirements for freshwater irrigation of biomass plantations are significant and a key factor determining the extent of their development in future. Development of biomass will also depend on the demands for water in different regions (See Box 7.3.).

7.3.5 Co-benefits and trade-offs

Bioenergy production is currently a significant source of income and jobs, employing over 3.5 million people globally (IRENA 2021). The conversion of biomass residues from agriculture and forestry, solid waste and sludge from municipal and industrial processes into fuel or electricity sources can transform potential environmentally harmful wastes into beneficial economic goods.

BECCS systems are designed to provide co-benefits that accelerate emissions reductions and concentrations by providing materials for the production of electricity or fuel, as well as sequestering carbon. Like hydropower and geothermal energy, this can also serve as a baseload to grid with solar and wind production. If implemented in a socially-ecologically sustainable manner, it can also enhance productivity of certain land uses and provide economic benefits and agricultural livelihoods. The very high demand for water and land however means that significant trade-offs need to be considered. Luderer et al. (2019) estimated that generating electricity from BECCS occupies 20 times more land area than hydropower, or coal with CCS, and two orders of magnitude more than wind and solar PV. Land-use changes can also lead to loss of natural wildlife, habitat, and reduced biodiversity. Creating biomass plantations is an intervention into ecosystem and landscape structure and functioning, and thus involves environmental impacts (Heck et al. 2016).

Projections on the potential for negative emissions that can be delivered from large-scale biomass plantations must consider the likely constraints faced by limited water and land availability in many regions (e.g., Heck et al. 2016). Investment in BECCS that seek only to maximize their potential for energy generation and carbon sequestration on existing land could result in global water withdrawals of up to 9,000 cubic kilometres per year by the end of the century – more than the current water use by agriculture, industry and households (Stenzel 2021). Demand for water and land for BECCS need to be evaluated to determine its potential implications and viability.

7.3.6 Potential implications for governance

As detailed above, climate mitigation contributions from large-scale biomass production may partly fail due to water limitations, or their implementation may adversely affect water availability. It is therefore imperative that water issues are considered in any deployment of such mitigation measures. This calls for integrative approaches that not only aim for maximizing negative emissions but also account for the preservation of aquatic ecosystems (such as in the European Water Framework Directive[1] or the Brisbane Declaration and Global Action Agenda on Environmental Flows[2]) and sustainable water management for both biomass plantations and agricultural areas. Integrative approaches can enable available water to be used more effectively, boost biomass production, and create synergies across multiple Sustainable Development Goals (SDGs), including targets for food, water, and climate security (Jägermeyr et al. 2017). Stenzel (2021b) highlights that substantial reductions in water withdrawals could be achieved if less plantations were irrigated and the carbon conversion efficiency was improved, thus enabling more production and sequestration with lower impacts on water. Large-scale field studies for the BECCS process chain are missing and are needed to fill the current implementation gap (Fuss and Johnsson 2021).

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1. Declaration, B., 2007, September. The Brisbane Declaration: environmental flows are essential for freshwater ecosystem health and human well-being. In 10th International River Symposium, Brisbane, Australia (pp. 3-6).
2. Directive 2000/60/EC of the European Parliament and of the council of 23 October 2000 establishing a framework for Community action in the field of water policy (OJ L 327, 22.12.2000, p.1).

Box 7.3. Assessing potential future constraints and applications of BECCS

Existing estimates of global freshwater quantities required for large-scale second-generation biomass plantations dedicated to BECCS, of either woody (e.g., willow, poplar, eucalyptus) or herbaceous (e.g., switchgrass, miscanthus) type vary significantly. These have been produced mainly from scenario studies that consider BECCS as part of a portfolio of climate change mitigation options. The studies explicitly or implicitly address the issue of freshwater requirements. A recent literature review of 16 available global model-based assessments found that estimates of water withdrawal for irrigation of BECCS plantations vary from 128 to 9,000 cubic kilometres per year (km^3/y) (Stenzel et al. 2021a); values for water consumption are of similar orders of magnitude. The large range originates from different model parameters and scenario set-ups.

A further study (Ai et al. 2021) concluded that constraints for irrigation water supply will limit the actual land available globally for sustainable development of BECCS much more than most scenarios currently predict. If land in areas with water stress and withdrawal of non-renewable water are removed from scenarios, the water demand of BECCS is limited to 300 km^3/y instead of around 1,400–3,900 km^3/y. This has significant implications on the mitigation potential of BECCS development in the coming years.

Stenzel et al. (2019) distinguished the contribution of different factors to the potential freshwater for irrigation of biomass plantations in a framework of systematic simulations with one global hydrological and vegetation dynamics model. The study considered, both singly and in combination: a) limits to water withdrawals imposed by environmental flow requirements (preserving a monthly minimum flow to maintain riverine ecosystems); b) different carbon conversion efficiencies; and c) sustainable on-field water management options including ambitious levels of water harvesting, soil conservation, and irrigation system upgrades on both biomass plantations and food-producing cropland. Current agricultural land and land worthy of protection were excluded as potential plantation areas. On the remaining land, either woody or herbaceous biomass plantations were assumed to grow if needed for achieving the sequestration demand and, if climatic conditions allowed, giving preference to plant types with high water-use efficiency.

The simulations showed that unconstrained withdrawals of available freshwater (scenario IRR) on the areas considered for irrigation of biomass plantations would result in a global water use of almost 2,400 km^3/y, if the plantations were to sequester 255 Gt carbon by 2100 (Figure 7.3). This would equal around 80 per cent of the sum of current agricultural, industrial, and domestic water withdrawals. Scenarios that account for environmental flow requirements or more effective water management suggest a lower pressure on freshwater systems of this mitigation option. Accounting for environmental flows (scenario EFRs) would reduce the withdrawal to slightly below 1,500 km^3/y; however, the water and land available under this constraint would not be sufficient to support irrigation to the extent required for meeting the plantations' expected contribution. If more effective water management was implemented in addition (scenario WM), values would somewhat increase again as more water would become available downstream, enabling the sequestration demand to be almost met. Substantial further reductions in water withdrawals to around 400–700 km^3/y could be achieved if less plantations were irrigated, and the carbon conversion efficiency was improved (Stenzel et al. 2019).

While these simulations elucidate some water-related trade-offs and co-benefits involved with bioenergy production, any further water use would come on top of (or compete with) the demand from other sectors (Figure 7.3). This will potentially increase overall water stress, which is already high in many regions of the world. To provide the context of regional and global water stress, Figure 7.4 highlights areas where irrigation for bioenergy production would increase existing water stress or newly introduce stress (defined as a withdrawal/availability ratio). The spatial patterns are derived from a further model- and scenario-based study by Stenzel et al. (2021a), in which – other than in the study referred to above – future land use was allocated based on an economic optimization of the agricultural sector including biomass plantations, with irrigated fractions of the plantations assigned afterwards.

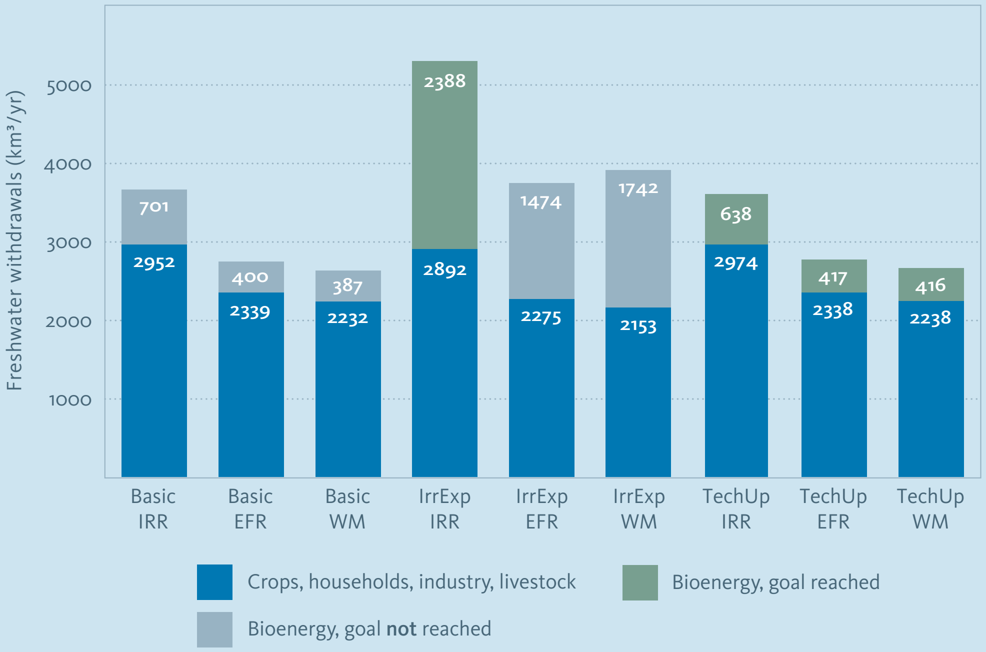

Figure 7.3. Annual (mean 2090–2099) freshwater withdrawal for irrigation of bioenergy plantations on top of withdrawals for agriculture/livestock, industries, and households, for different scenarios. Source: Stenzel et al. (2019). The assumed underlying total carbon sequestration goal of 255 Gt carbon (following a trajectory from 0.54 Gt carbon in 2030 to 5.45 Gt carbon in 2100, after Rogelj et al. (2015) required for limiting global warming to 1.5°C cannot be reached in all scenarios (green versus grey). The value for withdrawals in other sectors varies slightly among scenarios, as irrigation of plantations is simulated to compete with them. Improved water management (in some scenarios) is assumed to be applied on both the plantations and cropland. Baseline scenario (Basic): carbon conversion efficiency = 50 per cent and maximal irrigation fraction = 33 per cent; variants: in TechUp the former is 70 per cent, in IrrExp the latter is 100 per cent; while IRR assumes unconstrained withdrawals, environmental flows are respected in EFR, and WM additionally assumes improved water management.

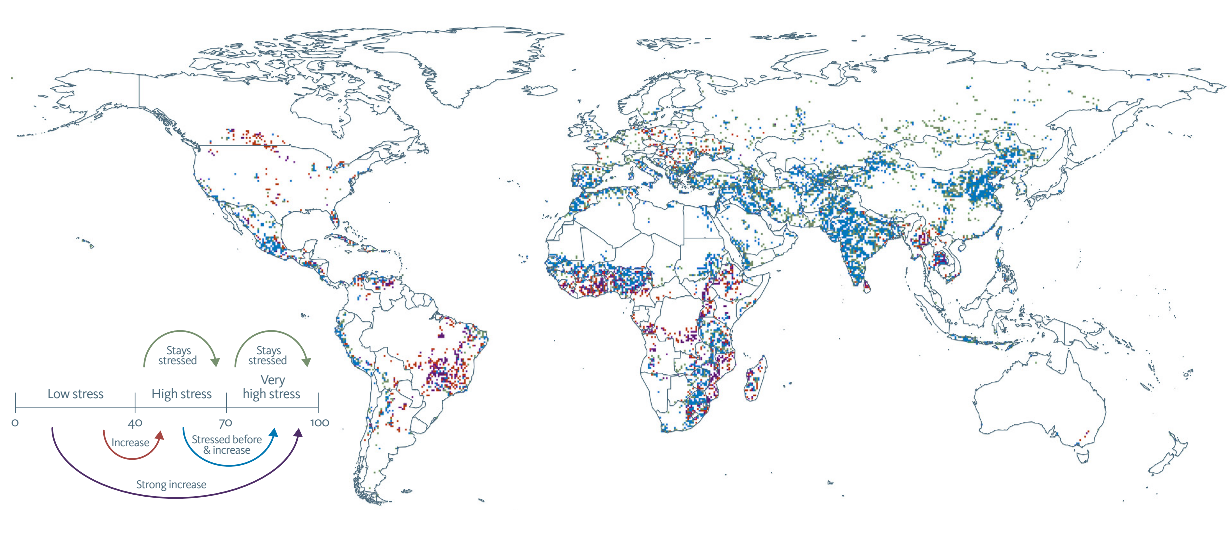

Figure 7.4. Regional changes in water stress class (mean 2090–2100) when adding irrigation of 30 per cent on BECCS plantations in an SSP2–RCP2.6 scenario (Frieler et al. 2017); total area, 616 million hectares under climate change according to the HadGEM2-ES model, after simulations from Stenzel et al. (2021a). Mean annual stress is calculated per 0.5°C grid cell as the percentage ratio of total water withdrawals (bioenergy, agriculture, industries, households) to available river discharge. Shown is where the water stress newly surpasses critical thresholds of 40 per cent (increase, orange colour) and 70 per cent (stressed before and increase, blue colour) respectively, surpassed both thresholds (strong increase, purple colour), or where it persists (stays stressed, green colour) compared to rainfed bioenergy.

Box 7.4. Green hydrogen and water

Hydrogen is an energy carrier, not an energy source. Hydrogen can be extracted from fossil fuels, biomass, or water (or a combination), and the emissions resulting from its use depend entirely on the source and the energy used in the process to extract it (similar to electricity). The global production of hydrogen accounts for 830 million tonnes of CO_2 emissions annually as the vast majority is produced using fossil fuel sources, e.g., coal and natural gas (IEA 2019). This is labelled as grey hydrogen if generated by fossil energies, or as blue if CCS is also applied. Blue hydrogen at present may not reduce the carbon intensity of energy use below that of natural gas (Howarth and Jacobson 2021). Green hydrogen, which is produced using renewable sources of clean energy, currently provides less than 1 per cent of total hydrogen production (IRENA 2020).

Currently, hydrogen energy is used mainly in industrial settings and produced with sources from natural gas and coal. Its future applications are envisaged in transport, buildings, and power generation (IEA 2019) using non-fossil-fuel sources and production processes powered by clean energies. It is anticipated that hydrogen will provide a critical element of future energy delivery systems in line with reduced emission targets. The European Union refers to green hydrogen as “the missing piece of the puzzle” in a fully decarbonized economy (EC 2020). Hydrogen is similarly characterized by IRENA in its global renewable energy outlook as a pillar for transformative energy futures, where they forecast exponential growth as a requirement for achieving zero net emissions targets by 2050. Current production levels for green and blue hydrogen energy are less than 2 million tons annually. An increase to 240 million tons by 2050 is required in the IRENA net zero scenarios (IRENA 2020). This would also require 7,500 TWh of annual renewable power producing hydrogen energy (raised from 0.26 TWh in 2016) and increased capacity of electrolysers to 1,700 GW (raised from 0.04 GW in 2016). Land and water demand for the electricity production required to synthesize hydrogen needs to be considered as this differs significantly between energy sources and dramatically effects the overall environmental impacts of the hydrogen produced (Mehmeti et al. 2018; Trainor et al. 2016).

Water also plays a crucial role in providing hydrogen when it is extracted through water electrolysis. Every unit of hydrogen generated in this way consumes an estimated 9 units of water (Webber 2007; Beswick et al. 2021). The amount of water required to realize the potential scale of the expansion of hydrogen energy may pose potential constraints or trade-offs between uses (Webber 2007; Beswick et al. 2021). Some studies note that large-scale expansion of hydrogen energy for use in urban areas could also lead to risks of competition with drinking water sources (Oldenbroek et al. 2016). Many scenarios project solar and wind power generation being stored in hydrogen and shipped as clean energy supplies over much larger distances than electricity networks can send (e.g., IRENA 2020). This has potential for relative water savings at global or regional levels, as solar and wind power generation require less water than most fuel alternatives (Beswick et al. 2021). However, this also requires solar and wind plants to be located near a water source. This can be done for offshore wind power, but this is projected to expand at a much lower overall rate, it is currently is more costly to build and operate, and it may require desalination if using seawater (Sayed et al. 2021). Some of the greatest potential for solar power is available in arid environments and access to water sources for water electrolysis may be limited (ESMAP 2020). This means that water will be an important factor in planning the potential expansion of green hydrogen in the future.

7.4 Geothermal energy

7.4.1 Mitigation potential

Geothermal energy derives from heat below the earth’s surface that is carried up by hot water and/or steam. Depending on its characteristics, geothermal energy can be used for heating and cooling purposes, and can be harnessed to generate clean electricity. However, high or medium temperature resources are needed for electricity, which are usually located close to tectonically active regions.

Geothermal energy is a renewable resource that can also serve as a baseload energy source for intermittent sources like solar and wind. Annual global production

Svartsengi geothermal power plant in Iceland. Source: Shutterstock.

of geothermal energy for electricity is under 15 GW, while providing 46,000 terajoules for heating (which is roughly the same as biogas used for heating) (IEA 2020a). It has very low CO_2 emissions, estimated by IRENA (2017) to be 8 grammes per kilowatt hour of energy produced.

There is considerable potential for expansion of geothermal power, as there is exponentially more energy contained within the heat inside the earth's surface than can be obtained with all the oil and gas resources on the planet (IRENA 2017). Annual growth of geothermal energy (about 3 per cent) is slower than alternatives such as solar and wind. Current costs for construction, inspection, and drilling, as well as the required detailed oversight of social and environmental risks, are slowing the expansion of geothermal plants.

7.4.2 Geographical distribution

Geothermal plants are located in areas with molten rock that are close to the earth's surface and so relatively easy to access. Indonesia holds as much as 40 per cent of global geothermal reserves with potential for development and has the largest planned expansion in the near future (Ayuningtyas et al. n.d.). Other nations where geothermal energy is most widely developed include Costa Rica, El Salvador, Iceland, Italy, Japan, Kenya, Mexico, New Zealand, Nicaragua, Philippines, Turkey, and USA (IRENA 2017).

7.4.3 Water dependence and impacts

Geothermal energy is derived from pools of water heated by magma below the Earth's surface, so it is directly water dependent. The operation of geothermal power plants also requires water. The amount of water depends on several factors, including the size of the plant, technologies used, operating temperature, and cooling process used. When water is used for cooling and re-injection, geothermal can be water resource intensive (see also concentrated solar power [CSP], nuclear, etc.). If geothermal fluids are used instead of external water resources, then water use declines significantly (Jin et al. 2019; Union of Concerned Scientists 2014). Considerable amounts of water can also be required during the drilling and construction phases. Jin et al. (2019) estimated the median water demand for geothermal energy was 1,022 litres per kilowatt hour, though the factors listed above lead to a considerable range of values.

Geothermal power plants can have impacts on both water quality and level of consumption. Several studies have raised water pollution and ecosystem degradation as significant environmental impacts of geothermal energy system development (Sayed et al. 2021). These can be caused by contaminated wastewater discharges and by thermal pollution effects (e.g., sudden discharge of warm or cold water into water bodies). Hot water pumped from underground reservoirs often contains high levels of sulphur, salt, and other minerals. This water is generally kept within a closed-loop system, but there are risks of contamination if this system fails (Bošnjaković et al. 2019). Potential risks with implications for surface- and groundwater include contamination of groundwater with drilling fluids (during the drilling process), depletion and warming of groundwater during the mass withdrawal operations, and contamination of groundwater and surface waterways in the disposal of waste liquids (from both surface disposal and reinjection processes) (Bošnjaković et al. 2019).

Some geothermal plants emit small amounts of mercury, which must be mitigated with appropriate filtering technologies. Scrubbers can reduce air emissions, but they produce a watery sludge composed of the captured materials, including arsenic, chlorides, mercury, nickel, silica compounds, sulphur, vanadium, and other heavy metals. This toxic sludge must be disposed of at hazardous waste sites (Union of Concerned Scientists 2014).

7.4.4 Co-benefits and trade-offs

Additional potential environmental impacts can result from geothermal energy and should be evaluated during planning, development, and operations. These include potential geological hazards (such as landslides or tremors), air pollution, land subsidence following removal of steam and mass fluids, land-use impacts and drilling that can cause disturbance to people and wildlife and damage biodiversity, and release of gases and solid wastes that can harm the health of workers and other people in the area (Sayed et al. 2021). Land-use changes required for the development of geothermal energy plants can also be significant. Examples that have prevented development in Indonesia, for example, include prospecting areas including conservation forests, ancestral land rights, impacts on local water resources, and cultural objections to drilling through land (Ayuningtyas et al. n.d.).

A key benefit of geothermal energy is its ability to provide a baseload for the grid to support the use of other intermittent renewable electricity technologies, such as wind and solar PV. Hybrid approaches can also be used to enhance efficiency and reduce land and resource requirements of the geothermal plants by, for example, using wind or solar PV to pump fluids, and solar thermal plants to heat the underground reservoirs.

7.4.5 Potential implications for governance

Well-managed geothermal energy generation provides an opportunity for low-emission energy development and is particularly abundant in certain regions. Due to significant potential environmental risks, thorough environmental impact assessments and continuous monitoring are necessary. Management and planning practices make a considerable difference to risk mitigation, including such issues as proper site allocation and placement of injection wells. Customized plant design is also needed to ensure that construction and operational guidelines are suited to the specific surrounding environment (Sayed et al. 2021).

7.5 Nuclear power

7.5.1 Mitigation potential

Nuclear power provides about 10 per cent of global annual electricity and 5 per cent of total energy supply, representing an approximate annual production of 700,000 kilogrammes of oil equivalent (IEA 2020a). Nuclear power does not create direct emissions from its operations, although the mining and refining processes of uranium ore and the construction of the power plant itself require energy, so creating indirect CO_2 emissions. According to an IPCC report (Bruckner et al. 2014), CO_2 emissions from nuclear power are 12 grammes per kilowatt hour, making it the second-lowest emitter (after wind power) of the major sources of electricity.

The World Nuclear Association (2019) states an ambition (entitled ‘Harmony’) to support the achievement of the Paris Agreement targets by increasing nuclear power production by 1,000 GW by 2050 to provide 25 per cent of global electricity. However, nuclear power presents certain environmental, social, and security risks that pose some of the starkest trade-offs and divergence of views from the global community on its role in the future energy mix. For these reasons, multiple global scenarios, such as the IEA net zero emissions by 2050 roadmap, forecast a lower expansion to keep nuclear at roughly 10 per cent of global electricity production (Rogelj et al. 2018; IEA 2021f).

7.5.2 Geographical distribution

Physical geography or regional climates and environments are not important factors in the development of nuclear power. There are over 30 countries with nuclear power plants, but not all are in operation. Most of the countries with nuclear power plants are located in Europe, North America, and East and South Asia. The countries with the largest generation are the USA, France, China, Russia, Korea, and Canada. The countries with the highest ratio of energy production from nuclear energy are France (70 per cent), Slovakia (53 per cent), Ukraine (51 per cent), Hungary (48 per cent), Bulgaria (40 per cent), and Belgium (39 per cent) (IAEA 2021).

7.5.3 Water dependence and impacts

Like other thermo-electric power plants, nuclear power generation involves boiling water to make steam and then using water to cool the steam after it runs through the turbine. For safety and cost reasons, dry cooling is not used in nuclear plants. Jin et al. (2019) found the median water use for nuclear power plants to be 2,290 litres per megawatt hour and that it is slightly more water intensive than all other thermo-electric types of plant. Reduced availability of water, caused in part by climate change-induced reductions in rainfall in some areas, is leading to increased frequency of nuclear power outages (Ahmad 2021). While several factors affect total water requirements, the largest factor is the type of cooling system chosen. Nuclear power with once-through cooling systems have been assessed as having the highest demand for water withdrawals since once-through cooling uses more water than recirculating systems (Ali and Kumar 2017). In some cases, seawater is used for cooling and this lowers freshwater demand significantly.

Water is also used in the fuel extraction process, which includes the mining, processing, milling, enrichment, and fabrication of uranium into fuel. Water-based storage pools may also be used for storage of nuclear fuel after it is used. Further, nuclear plants require access to large emergency sources of water (called ultimate heat sinks) in case of accidents, when a plant may be shut down and require continued cooling.

Thermal pollution (e.g., sudden discharge of warm or cold water into water bodies) harms water quality and ecosystem health (see Box 7.5.). Accidents or failures at nuclear plants (e.g., the Fukushima Daiichi nuclear power plant disaster of March 2011 in Japan), can lead to the discharge of radioactive waste or water into oceans and freshwater bodies, posing risk of significant harm to ecosystem and human health that can potentially last for decades (Lu et al. 2021).

7.5.4 Co-benefits and trade-offs

Like hydropower and geothermal power, a key benefit of nuclear energy is its ability to provide a baseload for the grid to support the use of intermittent renewable electricity technologies, such as wind and solar PV. There are also potential opportunities to capture and utilize heat generated at nuclear power plants for thermal, process, and district heating; however, social acceptance of this practice has limited its applications to date (Royal Society 2020). Radioactive materials and waste created through nuclear power generation and uranium mining pose significant potential risks to environmental and human health. Radiation exposure from direct discharges of radioactive waste result in long-term damage to ecosystems and communities (Luderer et al. 2019; Lu et al. 2021).

High perceived risk and moral opposition to nuclear power in segments of the population can lead to significant social costs or create political barriers to its uptake (De Groot and Steg 2010). The development of nuclear power can also have significant implications for global, regional, and national security, and there is generally a high correlation between the development of nuclear power generation capacity and the proliferation of nuclear weapons (Sorge and Neumann 2021).

7.5.5 Potential implications for governance

Water is a key consideration, constraint, and risk in the use and expansion of nuclear energy as a climate mitigation strategy. Nuclear power is relatively water intensive, and the construction, design, and management systems used affect the level of water use and the risks posed to water systems. There are many guidance materials on water management for nuclear operations. Assessments of water requirements and impacts on existing and new nuclear plant construction in mitigation strategies should be required and regulated. Precautions to separate water from reactors are needed in some systems and tight regulations are needed to prevent radioactivity from entering water sources.

Box 7.5. Water use in thermo-electric plants

Thermo-electric power plants generate electricity by boiling water into steam to power a steam turbine. Following this process, the exhaust steam must be cooled and then heated again. The cooling process can be wet (with water), dry (with air), or a hybrid (a combination of water and air). Van Vliet et al. (2016) estimated that over 80 per cent of global electricity generation came from thermal power plants.

When planning and developing plants requiring large volumes of water for cooling processes, availability and impact on water resources must be considered. Thermal pollution (e.g., sudden discharge of warm or cold water into water bodies) harms water quality and ecosystem health. Fish and other wildlife can also be killed when water is taken in from such natural sources as rivers and lakes (USC 2014). Worldwide, it is estimated that one third to one half of existing thermal power plants are located in areas of high water stress (IEA 2021g; Kressig et al. 2018). Multiple cases of power outages or reduced power generation capacity of thermal plants have been recorded in recent years and are regularly reported in mainstream media across all continents.

The water demand and impacts for thermal electricity generation vary slightly between coal, natural gas, nuclear, concentrated solar, and biomass powered plants (Jin et al. 2019). The type of cooling system used has the greatest impact on total water demand. Power plants with once-through cooling systems withdraw high volumes of water, and those that use steam turbines are even more water intensive. Adding recirculating cooling systems decreases water withdrawals and reduces vulnerability to potential constrained access to water. Dry cooling systems use air instead of water and remove water demands but are much less common due to their high cost. In the USA, for example, dry or hybrid cooling systems account for only 3 per cent of thermal generation plants (US EIA 2018) and are not viable for nuclear power plants. Ensuring the availability of cooling water for thermal energy generation under climate change is a key issue for the current and future resilience of energy services (IEA 2018). Beyond climate impacts on overall water availability, global warming impacts may also slightly increase cooling requirements for power plants (Yalew et al. 2020).

7.6 Solar and wind power

7.6.1 Mitigation potential

Solar power, along with wind, is the fastest growing renewable energy source, with continued exponential growth projected in all pathways to achieving the Paris Agreement targets. Current annual solar power electricity production is 582 GW, with annual added capacity per year exceeding 20 per cent growth. Global installed wind power in 2020 reached 743 GW, with an annual growth of 93 GW (GWEC 2021). Solar power accounted for 2 per cent of global gross electricity production in 2018 (IEA 2020b), and wind power is the fifth largest energy source contributing to electricity generation. It accounts for about 5 per cent of total global electricity generation (IEA 2020b), and 15 per cent of the total in Europe.

In nearly every projected pathway (see e.g IPCC 2022, IEA 2021g, and IRENA 2020) the expansion of solar and wind power to replace fossil fuel energy sources will provide the largest reduction in GHG emissions within the energy sector. IPCC (2022) projects solar and wind power as having the highest potential emissions reduction and cost-saving potential of all energy options. Solar PV and wind power each accounted for one third of the overall growth of low-emission energy sources in 2020 (IEA 2021f). Wind and solar power are also the primary technologies already on the market (and not in demonstration or prototype stages). In the IEA main case outlook for renewable energy growth between 2020 and 2025 (IEA 2021f), wind and solar power capacity will double, increasing by over 1,100 GW within 50 years. One key factor in this growth is a projection for solar PV utility generation costs to decrease significantly (by 36 per cent), making it a low-cost option in most countries (IEA 2021f). Still, considerably greater expansion is needed in annual capacity additions, from 134 GW in 2020 to 630 GW in 2030, as predicted in the IEA scenario for net zero emissions by 2050 (IEA 2021g). Record growth in 2020 and the expected increase in capacity additions in upcoming years will not be sufficient to ensure net zero levels.

The Global Wind Energy Council (GWEC) projects additional wind power installation of 469 GW based on its analysis of current pipelines and policy trends as well as continued reductions in costs, improved operations and maintenance, and reduced investor risk (GWEC 2021). Across most net zero scenarios towards the Paris Agreement targets, wind power increases from its current 6 per cent of global energy generation to over 30 per cent (GWEC 2021; IRENA 2020; IEA 2021g). IRENA projects wind power growth under current policy paths to reach 2,037 GW by 2030 and 4,474 GW by 2050. It also shows that to reach the Paris Agreement targets, even larger growth is needed of 3,227 GW by 2030 and 8,828 GW by 2050 (IRENA 2020).

Solar power is projected to expand even faster and to extend further than wind. Under current policy scenarios, IRENA (2020) estimated electricity production from solar PV to increase from 624 GW in 2020 to 1,455 GW by 2030 and 2,434 GW by 2050. To meet emission targets in the IRENA net zero by 2050 scenario, this rate would need to nearly double to reach over 2,500 GW in the next decade and more than 6,000 GW by 2050 (IRENA 2020).

7.6.2 Geographical distribution

Regions in lower latitudes and arid climates generally have higher natural potential for solar power. The World Bank Group, Energy Sector Management Assistance Program (ESMAP), and Solargis have produced the Global Solar Atlas, which evaluates regional solar power potentials. This shows the highest theoretical potential is located in Africa, Central America, the Middle East, and South America, with good potential also in South Australia, Southeast Asia, parts of Southern Europe, and the south-eastern United States. Currently, the largest and fastest-growing solar power producing country is China. Growth is seen worldwide, with the next largest producers in Brazil, Europe, and the USA (Figure 7.5.).

Wind power harnesses air currents to propel turbines that turn electric generators. A collection of turbines located together creates a wind farm, which needs to connect to a power network. Wind farms can be located onshore or offshore, the latter generally having higher capacity but also higher costs for construction and maintenance.

7.6.3 Water dependence and impacts

The transition to solar PV and wind technologies from other more water-intensive energy sources may provide an opportunity to reduce water use from the energy sector, and is often stated as a water-saving measure (GWEC 2021; US Department of Energy 2017).

All solar power technologies require small amounts of water for cleaning PV panels and other collection and reflection surfaces (Ali and Kumar 2017). Water resource requirements for production of solar PV cells,

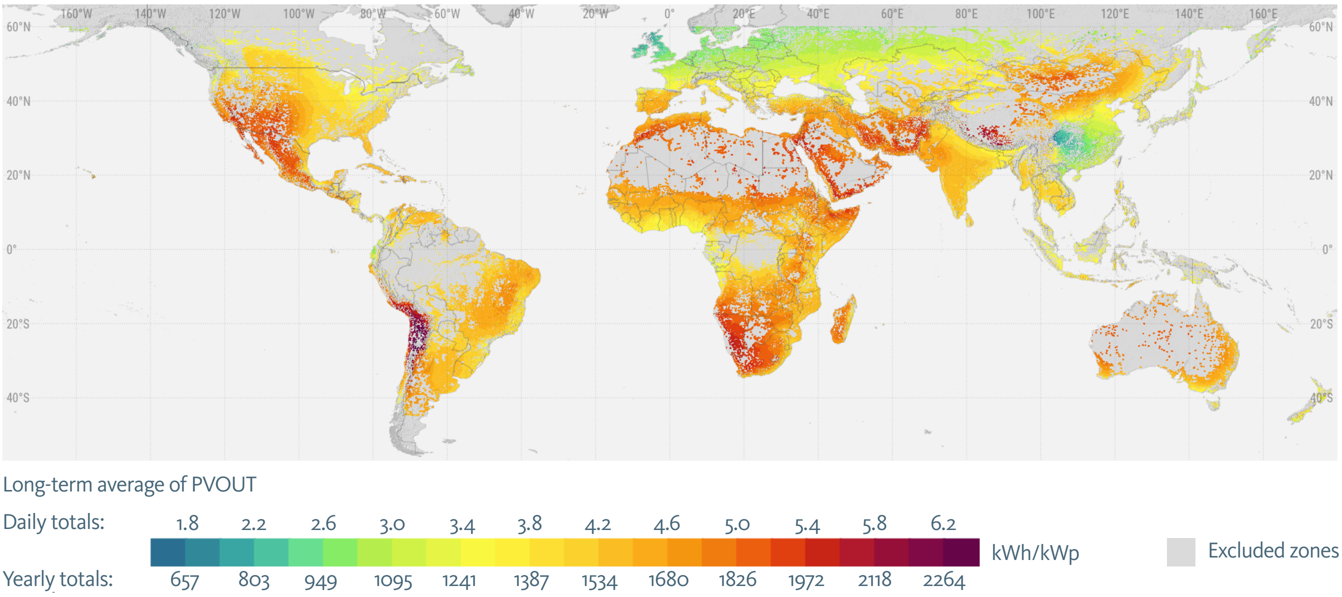

Figure 7.5. Global Solar Atlas projection of solar generation potential by region. Source: ESMAP (2020). Global Photovoltaic Power Potential by Country. Washington, DC: World Bank.

and construction of power plants where used, may need to be considered as they can impact water sources at the site of their production (Jin et al. 2019). Lohrmann et al. (2019) estimated that solar PV technologies require between 2 and 15 per cent of the total water per unit of energy produced compared with nuclear and coal thermal power plants. Production of crystalline silicon PV panels, however, can be relatively water and energy intensive to manufacture (Meldrum et al. 2013). The highest requirements for water from solar power occur in concentrated solar thermal power plants, where water use is similar to that of other thermal power production processes (Jin et al. 2019). Wet processes are most common (due to price and efficiency) for CSP plants, but are water intensive, generally requiring more than 2,000 litres per megawatt hour (Solar Energy Industries Association n.d.). Some solar thermal systems may also contribute to thermal pollution and may use potentially hazardous fluids to transfer heat, which if leaked are harmful to ecosystems (US EIA 2020).

The direct operations of wind power plants require relatively little water (Ali and Kumar 2017). Jin et al. (2019) found the median water requirement for wind power was 43 litres per kilowatt hour, which was the lowest water demand of all reviewed energy sources. Magnets made with rare-earth minerals have significant advantages for enhancing efficiency and lowering costs of turbine operations and are used in more than 75 per cent of offshore wind power globally (Alves Dias et al. 2020). Mining for rare-earth minerals used for magnets in wind turbines can, however, have significant environmental impacts, including on freshwater ecotoxicity and, in some cases, can contribute to eutrophication and acidification (Elshkaki 2021).

7.6.4 Co-benefits and trade-offs

There are several potential economic, health, and environmental co-benefits to the expansion of solar and wind power. Wind and solar PV are the most feasible energy options with the lowest requirement for and impact on water resources. They are thus critically important components of the energy mix to lower pressure on freshwater ecosystems. Wind and solar power also generate less air pollution than fossil fuel sources. Expanded investment in wind and solar PV is currently driving economic growth and employment, with nearly five million people employed in solar power industries and 1.25 million in wind power in 2020. Under clean energy transition scenarios to meet the target to limit global warming to 1.5°C, IRENA projects future employment of 20 million people in solar and more than 5 million in wind power industries by 2050 (IRENA 2021).

There are also several trade-offs and challenges concerned with reducing the negative impacts. Materials and production processes to construct solar panels require significant energy, and can have implications on water, land, and emissions (Elshkaki 2021). Emissions from copper processing, silicon refinement, and chemicals used in the production of solar panels can create toxicity and have negative impacts on human health (Giurco et al. 2019). Expansion of solar PV and wind power also increases requirements for electricity storage and batteries, creating a large increase in the demand for minerals, including aluminium, cadmium, cobalt, copper, gallium, graphite, indium, iron, lead, lithium, manganese, nickel, silica, silver, tellurium, tin, and zinc (Elshkaki 2019; Giurco et al. 2019). Stable supplies and mining of these materials used widely in clean energy technologies can also depend on the availability of high-quality water resources.

Magnets for wind turbines can also significantly increase demand for rare earth minerals, requiring up to two tons for large direct drive turbines. Mining of these materials can lead to numerous negative impacts on environment, health, equity, and human rights, as well as impacts on water quality and scarcity (Mancini and Sala 2018). Impacts can include poor worker safety; conflict over land rights; labour rights violations; air, soil, and water pollution; and biodiversity loss (Corneau 2018).

7.6.5 Potential implications for governance

Expansion of solar and wind power, and efficiency improvements account for meeting as much as 50 per cent of energy demand by 2050 in several scenarios to meet the Paris Agreement targets. If these are not reached, there is likely to be greater demand and pressure placed on water resources from all other alternatives. While solar PV is less water intensive than alternatives, CSP may require significant water resources for cooling, and life-cycle requirements for raw materials to produce solar panels must be understood so they can be sourced sustainably.

Hybrid power plant at Palm Springs, California, with solar PV and wind turbines. Source: Shutterstock.

Solutions for energy storage and flexibility are critical to enable energy systems that are reliant on variable energy sources such as wind and solar PV. Water implications of those solutions can be large. Most current energy storage solutions are provided by pumped hydropower, which has greater capacity for energy storage for longer periods of time than batteries (see section 7.2). There are potential solutions for pumped hydropower that use closed-loop systems between existing reservoirs that avoid impacts to larger river systems. Expansion of mining of minerals (e.g., cobalt, copper, graphite, lithium, silicon), as well as rare earth materials used in the construction of batteries, fuel cells, grids, magnets, and solar cells will also require stringent oversight and serious investment to prevent contamination of surface- and ground-water sources, as well as negative impacts on human and environmental health (Elshkaki 2021). OECD (2019) cited impact areas for risk mitigation to include accidents endangering works, dam failures, exposure to hazardous substances, and air pollution, as well as land and water pollution. It also notes many countries with rich mineral resources lack regulatory structures and capacity for risk mitigation in these areas as well as data and oversight of risks and environmental impacts of mineral mining across the supply chain.

Distributed solar PV and wind power are variable energy sources and can require investments and measures to improve overall power system flexibility and grid infrastructure (IEA 2021g). This flexibility can be provided by hydropower, geothermal or nuclear power. Each of these options, as discussed in this chapter, requires effective management to reduce water risks and impacts.

7.7 Conclusion and outlook of water, climate and energy production

Fossil fuel energy production requires significant water resources. Roughly 70 per cent of the water used by the energy sector, excluding hydropower goes to the production of fossil fuels and thermal power generation plants (IEA 2018). Total water withdrawals and consumption will need to be reduced significantly to reach the SDG targets with available resources.

The transition to renewable energies can provide opportunities to reduce pressure and impacts on water sources from the energy sector. The variation in the demand and pressure placed on water sources can vary dramatically depending on the future energy mix and its water management. There is a risk that renewable energy production will increase demand and pressure on water, as well as potential water risks that could constrain some options for renewable energy development in different regions. Low-emission energy generation that requires the operation of thermal power plants (geothermal, CSP, nuclear) are highly dependent on water and must be managed to ensure access and impacts on water sources are sustainable. Potential impacts and constraints on water sources are also critical to consider for the type and amount of bioenergy and hydropower involved in mitigation strategies.

Scenarios for future energy use that meet zero emission targets by 2050 (IEA 2021g; IRENA 2020; Rogelj et al. 2018) place the lion's share of the transition on expanding solar and wind power and making huge strides in energy efficiency and demand management. They are also heavily dependent on the uptake of technological innovations that are still in demonstration or prototype stages, including BECCS and green hydrogen (IEA 2021f). Similarly, clean energy transitions can have positive impacts on human and environmental health as reduction in burning of fossil fuels will lessen air pollution and toxic leaching from coal mines (Luderer et al. 2019). However, nuclear, hydropower, geothermal, bioenergy, solar, and wind power production are not free from side effects or dependencies, which should be weighted in assessments and investments in energy production. For example, ecosystem impacts from land-use changes required for the development of fuels, electricity generation, and the electricity grid need to be taken into account (Luderer et al. 2019). These assessments can also point to better solutions, for example, through closed-loop pumped hydropower systems to provide energy storage as part of solar and wind power networks.

Most projections for the energy transition also speculate on the expansion of green hydrogen, converters, and electric transport to fulfil and reduce the need for carbon fuels. Access and proximity to water is a fundamental requirement for hydrogen, which would mean that conversion of solar or wind power to hydrogen cells also needs to be located near and use water sources. Most pathways of electrification of transport project massive upscaling of battery production (IEA 2021g; IRENA 2020). Non-fossil mineral depletion, and impacts from its mining and extraction, pose risks for environmental damage and constraints to development, particularly for energy storage, as well as for nuclear, solar, and wind power. If solar or wind power are constrained, there may be significant implications for water resources and ecosystems as alternatives such as nuclear, geothermal, hydropower, and bioenergy can have higher overall impacts on water, and environmental and human health. Moreover, the demands and/or impacts on water sources for hydropower, bioenergy, nuclear, and geothermal may limit their sustainable expansion, where risks to ecosystems, biodiversity, and human health and security need to be considered. There are also additional water risks that will require more regular and comprehensive assessment to ensure clean energy transition, particularly with the production of fuels for transport and heating.

Access to energy in the future is projected to expand worldwide. There are an estimated 768 million people without access to electricity, and as many as half of the people in the world live in places that do not have access to sufficient electricity to fulfil basic development needs (IEA 2021d). Many regions must balance high water stress, population growth, economic development, and expansion of energy access (Oki and Quiocho 2020). While providing basic electrification adds relatively little to total energy demand, expanding energy generation in water-stressed regions will be an essential, unavoidable challenge to face, and must consider potential trade-offs with other demands for water resources that will follow national development.

Thus, in all energy planning, in both projected and known developments, water is an essential element that must be integrated across all aspects of development. This must be done while the transformation to clean and renewable energies is accelerated. The decline in economic activity and travel following the Coronavirus 2019 pandemic led to a 5.8 per cent reduction in emissions from the energy sector in 2020, which is the largest in modern history by a considerable margin (IEA 2021c). In 2021, however, global energy-related CO_2 emissions were estimated to rise by 1.2 billion tons, the second-largest annual increase in CO_2 emissions in history. This was due largely to a rebound in coal and oil use. Strong commitment and at least USD 4 trillion of annual investment in clean energy transitions and infrastructure are needed to change the course again and ensure that emissions trends in the energy sector move in line with achieving net zero targets by 2050 (IEA 2021g). For these investments and commitments to succeed, it is critical to account for linkages between water, energy, and climate security.

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