TNA TECHNOLOGY NEEDS ASSESSMENT

Technologies for Climate Change Mitigation in Developing Countries: Renewable Energy

UN environment programme | copenhagen climate centre

United Nations Climate Change
Technology Executive Committee

UNIDO
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List of Abbreviations

AC	Alternating Current
ADMS	Advanced Distribution Management Systems
AEM	Anion Exchange Membrane
AI	Artificial Intelligence
BECCS	Bioenergy with Carbon Capture and Storage
BoP	Balance of Pant
CO_2	Carbon Dioxide
CSP	Concentrating Solar Power
CTCN	Climate Technology Centre and Network
CVR	Conservation Voltage Reduction
DC	Direct Current
DLR	Dynamic Line Rating
EGS	enhanced geothermal system
FACTS	Flexible AC Transmission Systems
gCO_2eq	Grams of CO2 equivalent
GHG	Greenhouse Gas
GW	Gigawatt
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
kW	Kilowatt
kWh	Kilowatt/hour
LCOE	Levelised Cost of Electricity
LDC	Least Developed Country
LFP	Lithium Iron Phosphate
MW	Megawatt
MWh	Megawatt/hour
NDC	Nationally Determined Contribution
OTEC	Ocean Thermal Energy Conversion
PEM	Proton Exchange Membrane
PFC	Power Flow Controllers
PHS	Pumped Hydro Storage
PSH	pumped storage hydropower
PV	Photovoltaics
SET	Strategic Energy Technology
SDG	Sustainable Development Goal
SGE	Salinity Gradient Energy
SIDS	Small Island Developing States
TEC	Technology Executive Committee
TNA	Technology Needs Assessment
TWh	Terawatt/hour
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
UPFC	United Power Flow Controller
USD	US Dollars
VVO	Voltage/VAR Optimisation
WACC	Weighted Average Cost of Capital

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Foreword

The energy sector is the largest contributor to global greenhouse gas emissions. Accelerating the deployment and scaling up of zero- and low-emission energy technologies is therefore critical. The outcomes of the first global stocktake under the Paris Agreement have emphasised the pivotal role of renewable energy in achieving deep, rapid, and sustained reductions in greenhouse gas emissions, aligned with the temperature goal of the Paris Agreement.

Technology Needs Assessments (TNAs) assist countries to identify and prioritise technologies needed for climate change adaptation and mitigation in different sectors, and to formulate related implementation pathways. Actions in support of TNAs and the implementation of their outcomes are at the core of the work on technology development and transfer under the UNFCCC and the Paris Agreement, in particular through the work of the Technology Mechanism, guided by the technology framework.

In 2023, the Technology Executive Committee (TEC) conducted an assessment of gaps in existing TNA guidance and identified, among other things, the need for the development of a guidebook on mitigation technologies for the energy sector. The TEC has benefitted from a collaborative partnership with the United Nations Industrial Development Organization (UNIDO) and UNEP Copenhagen Climate Centre (UNEP-CCC) to address this gap by developing this guidebook.

The TNA guidebook on renewable energy comes at an opportune time with the communication of the new round of nationally determined contributions (NDCs) under the Paris Agreement in 2025 after its first global stocktake, and the initiation of the latest phase of the Global TNA project – TNA Phase V, engaging seventeen partner countries.

This guidebook provides practical guidance to developing countries conducting or updating their TNAs, with the aim of achieving net zero emission in energy supply, energy storage, energy transmission and distribution. It highlights technology options, enabling conditions, barriers and good practices. It also includes aspects of just transition.

TEC, as part of its mandate, continually monitors the TNA process and its results and conducts policy-focused work to support countries to enhance the effectiveness and utility of the TNA process, in line with their national priorities and long-term goals of the Paris Agreement.

With its mission to pursue inclusive and sustainable industrial development, UNIDO promotes and accelerates transforming industrial sectors which contribute significantly to global greenhouse gas emissions. This involves accelerating the development and deployment of low- and net zero emission technologies including transforming to renewable energy.

UNEP-CCC, on behalf of UNEP, has been responsible for executing the GEF-funded Global TNA project in over 100 countries since 2009. Through the TNA process, national TNA teams develop their TNAs and Technology Action Plans (TAPs) for selected priority sectors, outlining challenges for key technologies as well as pathways for their successful deployment and uptake.

We believe this guidebook, along with other sectoral and process-related guidance on TNA, could serve as a valuable resource for technology practitioners and national TNA teams to inform their technology choices and advance a rapid and just transition to climate-resilient and sustainable energy systems.

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Executive summary

This guidebook is part of a series of Technology Needs Assessment (TNA) guidebooks supporting country teams and practitioners in identifying and prioritising climate technologies for adaptation and mitigation by focusing on specific sectors. The guidebook provides an overview of up-to-date information on a wide range of relevant renewable energy technologies that can be considered in developing the countries' TNAs, individually or in combination, depending on the specific national circumstances and in line with development and climate priorities.

Solar photovoltaic (PV) has become the most cost-competitive renewable energy technology, with utility-scale project costs falling 90% since 2010. In 2023, it saved USD 20 billion in fossil fuel costs and is projected to become the world's cheapest electricity source by 2030. Despite this, high upfront costs and uneven financing conditions continue to limit uptake in many regions.

The adaptability of solar PV can be utilised to expand electricity access, particularly in remote areas. At the same time, environmental and social impact assessments can inform project siting to minimise land and water conflicts. Integrating job training will help ensure equitable employment benefits and a just transition, while capacity building efforts are critical to secure the long-term technical and financial sustainability of this technology in isolated and communities.

Wind technology can play an equally important and complementary role to Solar PV. It is a clean technology with extremely low lifecycle emissions and short carbon payback periods, and complements solar PV seasonally, reducing reliance on storage. This technology includes traditional geared systems and emerging direct-drive turbines, with the latter reducing maintenance needs but increasing reliance on rare earth materials. Onshore wind is cheaper and easier to install, while offshore wind offers higher and more consistent energy output.

Floating offshore wind can expand siting options, especially for countries with deep coastal waters. Environmental and social assessments are critical to mitigate impacts on biodiversity and local communities. Permitting bottlenecks and financing disparities remain major deployment barriers, especially in developing countries. Just Transition policies can support community consultation, fair land compensation, and job creation through local hiring and training.

Both wind and solar PV, despite their modularity and versatility, face issues related to intermittency that can be complemented with storage options or with more stable renewable energy sources. Hydropower can perform a balancing role to solar PV and wind. This technology is known for its ability to provide grid balancing and frequency regulation, especially through pumped storage. Despite these strengths, it has high upfront costs and long lead times, as well as major environmental and social impacts on ecosystems and communities especially in its large-scale capacity.

Climate change threatens hydropower's reliability through increased droughts and variable rainfall, requiring new adaptive infrastructure, and its costs have risen in recent years, driven by projects encountering complex engineering demands and difficult site conditions. A just transition requires respecting land rights, offering fair compensation, and maximising local development benefits. Smaller-scale hydro offers employment, training, and energy access, especially when paired with local manufacturing. For future viability, hybrid solutions with solar PV and climate-resilient designs should be considered.

Other renewable energy sources that can play a complementary role include biomass, geothermal, and marine. Biomass can co-fire with fossil fuels or operate independently as baseload power. It is theoretically carbon-neutral but creates CO_2 accounting challenges, especially when feedstocks are transported long distances – coupling the technology with bioenergy with carbon capture and storage (BECCS) can deliver negative emissions, though the technology is costly and underdeveloped. Costs can vary significantly, with varying feedstock prices affecting levelised cost of electricity (LCOEs) substantially, and climate change may threaten feedstock availability, so adapting crop practices and sourcing waste residues will be key.

Geothermal energy is a reliable and continuous energy source suitable for baseload but has so far been limited geographically, although new technologies such as Enhanced Geothermal Systems and others can expand this technology's reach and reduce its costs. Marine energy remains nascent, with a negligible installed capacity so far, but with large potential. It offers predictability in its tidal form, and seasonal complementarity with offshore wind, but still faces technological and cost challenges.

Energy storage will be an additional and key tool to balance variable renewables. It comes in numerous forms: pumped hydro dominates today thanks to its low cost and long duration, but battery storage is rising rapidly, led by lithium-ion and newer chemistries. In contrast to pumped hydro, utility battery storage offers modularity and has a wider geographical reach, adapting to mini-grids. Moreover, it offers fast ramping. It faces however raw material and regulatory challenges. Thermal and geothermal storage provide sector coupling, long lifespans, and seasonal capabilities, though they suffer from low maturity and limited policy support. Green hydrogen finally can offer long-term, system-wide storage potential and industrial decarbonisation. High costs, efficiency losses and infrastructure gaps concerns however hinder its future deployment.

Together with integrating renewable energy sources with storage solutions, modernising the grid will be essential for integrating variable sources like solar and wind. The technologies envisaged and provided in the guidebook enhance grid flexibility, efficiency, reliability, and resilience. At the same time, they allow for reduced outages and higher renewable penetration, while deferring otherwise necessary infrastructure investments. Economic and environmental gains include avoided curtailment, fewer emissions, and lower transmission losses, though barriers remain in cost, data complexity, regulatory gaps, and skilled workforce needs.

A diverse mix of renewables, storage and grid modernisation can help countries carry out a successful energy transition. This, coupled with inclusive planning, local job creation, and protections for affected communities, can contribute to a just energy transition, while promoting sustainable growth, energy security, and social progress.

1. Introduction

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1.1. The importance of the energy sector for climate mitigation

On the occasion of the first global stocktake of the Paris Agreement, which concluded in 2023 at COP28 in Dubai, the Parties to the Paris Agreement further recognised the need for deep, rapid and sustained reductions in greenhouse gas (GHG) emissions, in line with 1.5°C pathways. This called for the Parties to contribute nationally to global efforts to reduce GHG emissions, with the intent of achieving the following energy-related emissions targets, as mentioned in Decision 1/CMA.5 (UNFCCC, 2024):

- Tripling renewable energy capacity and doubling the global average annual rate of energy efficiency improvements by 2030;
- Accelerating efforts towards the phase-down of unabated coal power;
- Accelerating efforts globally towards net zero emissions energy systems, utilising zero- and low-carbon fuels, well before or by around mid-century;
- Transitioning away from fossil fuels in energy systems, in a just, orderly and equitable manner, accelerating action in this critical decade, so as to achieve net zero by 2050 in keeping with the science;
- Accelerating zero- and low-emission technologies, including, inter alia, renewables, nuclear, abatement and removal technologies such as carbon capture and utilisation and storage, particularly in hard-to-abate sectors, and low-carbon hydrogen production;
- Accelerating the substantial reduction of non-carbon-dioxide emissions globally, in particular methane emissions by 2030.

The energy sector is, by far, the largest contributor to GHG emissions released annually into the atmosphere. In 2023, it contributed to approximately 68% of total GHG emissions, with the power sector alone being the largest single contributor at approximately 26% (UNEP, 2024). Emissions in the power sector are released mainly from the burning of fossil fuels for electricity generation, while some are due to fugitive emissions and the carbon footprint of the extraction and distribution of the fuels used.

According to the International Energy Agency (IEA), the largest global fossil fuel contributors in 2022 were coal, peat, and oil shale, accounting for more than 70% of all emissions in the power sector, followed by natural gas and, in smaller quantities, oil and waste (IEA, 2024c).

These global figures hide large disparities between countries, with the power sector contributing varying shares of GHG emissions depending on the composition and structure of a country's economy. Evidence suggests that economic and human development go hand in hand with an increase in energy consumption and in electricity demand (Herre & Arriagada, 2023; Ritchie, Rosado & Roser, 2023).

There is a diverse array of renewable energy technologies to minimise GHG emissions while countries advance their economic and human development. Each of these technologies comes with advantages as well as drawbacks, which should be taken into consideration to balance reliability, cost, as well as the social impact of electricity generation, and ensure that nobody is left behind in the process.

1.2. The Technology Needs Assessment guidebook

This guidebook is designed to assist technology practitioners and national Technology Needs Assessment (TNA) teams as they select the appropriate energy source to generate, store and distribute power in their countries.

In providing these detailed guidelines, this guidebook aspires to:

1) Provide a catalogue of existing technologies available to each country.
2) Provide a ready-set range of parameters to consult and measures to undertake when deploying each technology, including the elements to consider for a Just Transition of the workforce[1].
3) Offer a catalogue of information on prices and available open-source material to support the reader.

1 The aspects of Just Transition considered in this guidebook are delineated in the guidelines presented by the International Labour Organisation (ILO). In the Technical Paper: "Just Transition of the Workforce, and the Creation of Decent Work and Quality Jobs", governments are provided with the elements to consider for a Just Transition of their workforce when adopting climate mitigation technologies.

The adoption of such technologies depends on different national circumstances such as the level of economic development and well-being, or urbanisation rates and available space. Other factors influencing these decisions will include geographic, climatic and weather conditions, as well as availability of resources and human capital. For example, countries belonging to the Least Developed Countries (LDCs) and Small Island Developing States (SIDS) groupings often require solutions tailored to their needs.

This guidebook focuses on energy supply from renewable sources, energy storage, and energy transmission and distribution. It does not cover heat supply technologies, technologies from the demand side, or from a sectoral perspective. Corresponding guidebooks for Agriculture, Buildings and the Transport sectors have already been published. Future guidebooks may cover technology options for energy-intensive industries, for industrial energy efficiency, for household energy use, as well as an update for energy options in the transport sector. For a more detailed explanation of the TNA process, see the TNA Step-by-Step guidebook.

1.3. Complementary resources

This guidebook leans on the support of resources gathered from the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), and government resources such as national energy reports and energy development strategies. In addition to these main points of reference, the guidebook utilised a number of other sources to enrich and expand its analysis. The list of these resources will be provided in Appendix III (Additional sources of information on mitigation technologies and practices) and Appendix IV (Further reading) of this guidebook.

1.4. Structure of the guidebook

The guidebook is structured as follows:

Chapter 2 includes an overview of the interaction between energy and climate change, explaining how energy production, transformation and consumption contribute to releasing GHG emissions into the atmosphere.

Chapter 3 covers the core of the guidebook and focuses on an array of available technology options for climate change mitigation. It constitutes the bulk of the guidebook, and analyses each available technology option in terms of their advantages and disadvantages, while also providing an economic assessment and a view of their affordability. For each technology option, the guidebook also explores their mitigation and net zero potential, aspects related to Just Transition, and ways to enhance these technologies' resilience to climate change. Finally, there is an overview of the barriers to dissemination and deployment, in addition to real-world examples that may showcase how best to deploy the preferred technology options. The aim of this chapter is to inform national teams assessing their preferred technology measures, in response to contextual factors and their national circumstances.

Chapter 4 presents conclusions, recapping the main challenges and opportunities in energy supply technologies and climate change mitigation, including aspects of Just Transition.

The guidebook also includes appendices with a summary sheet, a glossary, additional sources to consult and further reading.

2. Overview of climate change and energy

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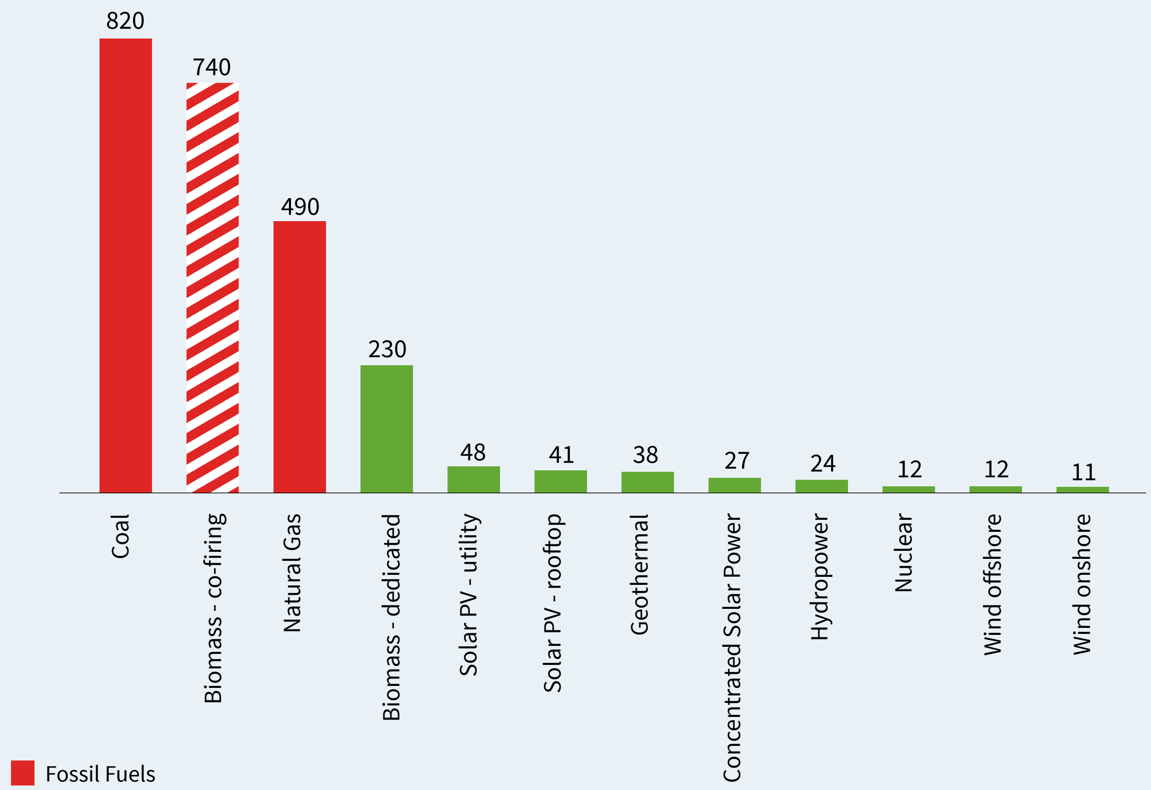
The energy sector is the single largest global contributor to GHG emissions, with the power sector representing the largest share of the total. It is also an essential cornerstone of economic development, well-being and economic activity. It is therefore essential to act on this sector to mitigate climate change, especially as its role is bound to grow in the coming decades due to the accelerating distribution of electric house appliances, electric vehicles and even industrial processes powered by electricity.

On the one hand, implementing policies and deploying technologies to decarbonise the power sector is a relatively straightforward endeavour, compared with other components of the energy sector. At its final use, electricity is a clean form of energy, which means that most actions need to be focused almost exclusively upstream, at generation, at the power station level, with some gains also possible in transmission, distribution, storage and energy carriers.

By far the main culprit for this sector directly releasing GHG emissions into the atmosphere are fossil fuels burned for electricity generation (Figure 2.1). Coal and natural gas, for example, release respectively 3.5 and 2 times as much as much CO_2eq/kWh generated as the next-highest renewable energy source (biomass), and up to 17 and 10 times those released by solar (Schlömer et al., 2014). Emissions can also be released, indirectly, through infrastructure and supply chains (including for otherwise clean energy sources). Methane from the procurement of natural gas, as well as that released during the running of hydroelectric dams, is also a secondary source of GHG emissions, together with highly potent SF_6 gases used in switchgear and transformers.

Figure 2.1: Median life cycle emissions per source of electricity generation (gCO_2eq/kWh)



Note: Coal and natural gas, together with co-firing of biomass with coal, are the three top emitting sources for electricity generation. This is taking into account both direct greenhouse gas emissions and indirect emissions from supply chains.
Source: Schlömer et al., (IPCC), 2014

Due to the emissions intensity of fossil fuels at generation, their replacement with cleaner electricity sources is the fastest way to reduce emissions from the power sector.

In this regard the Paris Agreement was instrumental in providing essential political support on a global scale for the impressive progress in renewable energy adoption that has been witnessed since 2015. As stated in UNFCCC's Synthesis Report on Nationally Determined Contributions (NDCs), 94% of countries provided quantified mitigation targets whereas 80% communicated economy-wide targets (UNFCCC, 2023). Moreover, if we include mitigation options with the highest estimated net emission reduction potential, 50% of the Parties communicated measures to promote solar energy, and 36% did the same for wind energy. The Parties have been attentive to include just energy transition measures in their NDCs: 65% highlighted policy coherence and synergies between mitigation measures and development proprieties, 79% referred to arrangements for domestic stakeholder consultation, and 33% affirmed their intention to take gender into account when implementing their mitigation measures (UNFCCC, 2023).

In the same report, the Parties expressed technology needs for mitigation options (33%), while 13% of them referenced the need for technology action plans to identify priority technology needs. This guidebook aims to respond to these needs and to maintain the necessary momentum to achieve 1.5°C reduction pathways.

Extraordinary progress has been achieved in the deployment of renewable energy sources, especially in the last ten years, however, there is still much to be done as highlighted also by the United Nations Environment Programme (UNEP)'s Climate Technology Progress Report 2024. Today, 60% of global electricity generation is still derived from coal and natural gas (UNEP, 2024), and the IEA estimates that this share will need to decrease to 30% by 2030 to keep the power sector on a path towards net zero emissions by 2050 (IEA, 2023b). This is an incredibly important point, because reaching net zero emissions by 2050 is the identified path towards limiting global warming to sustainable levels.

2.1. Transitioning to net zero and renewable energy sources

The most recent report from the Intergovernmental Panel on Climate Change (IPCC, 2022) states that to limit a global temperature rise to 1.5°C compared to pre-industrial levels by 2100, the global net release of GHG emissions into the atmosphere must reach zero by 2050.

The report indicates a higher frequency of extreme climate and weather events in the time during which a rise in average global temperatures of 0.5°C has been observed. It then proceeds to state that limiting temperature rises to 1.5°C would result in a reduced probability of extreme drought and in reduced levels of stress on water systems and water availability. Moreover, it would result in diminished risks to "natural and human systems", which would allow them to adapt better and faster to the effects of climate change. Average temperature rises above 1.5°C and below 2°C already put both natural ecosystems and human civilisation under excessive stress and should be avoided.

At the same time, the report indicates that the mitigation pathways necessary to achieve net zero emissions by 2050, and thereby to limit an average global temperature rise to 1.5°C, risk being implemented at the cost of significant trade-offs in terms of sustainable development goals (SDGs). Countries must therefore be able to balance decarbonisation efforts and costs with other national development considerations, including through a Just Transition lens. Social protection should be included in energy transition policies. Communication between the public and private sectors and local communities must also take place, through the form of a tripartite dialogue between government, workers and businesses.

2.2. Elements to consider for the Just Transition

Although there is no agreed upon definition of the 'Just Transition', the term is broadly understood to refer to efforts to ensure that, within the process of transitioning the global economy to a low-carbon structure, any negative social, environmental or economic impacts of the transition are minimised, while benefits are maximised. The term is also understood to include promotion of a 'people-centred' approach to the design and execution of the energy transition. The IPCC cites the following core elements of the Just Transition in the sixth assessment report (2022):

- Early assessment of the social and employment impacts of climate policies;
- Social dialogue and democratic consultation of social partners and stakeholders;
- Creation of decent jobs, active labour market policies and rights at work;
- Fairness in energy access and use;
- Economic diversification based on low-carbon investments;
- Realistic training and retraining programmes that lead to decent work;
- Gender-specific politics that promote equitable outcomes;
- Fostering of international cooperation and coordinated multilateral actions;
- Redressing of past harms and perceived injustices;
- Consideration of intergenerational justice concerns, such as the impacts of policy decisions on future generations.

In recent years, the conceptualisation of 'Just Transition' has evolved from a principally worker-focused approach to a broader effort towards the promotion of the well-being of communities and the mitigation of negative social or ecological impacts within the energy transition.[2] An energy transition can generate trade-offs in terms of SDGs. For example, solar PV and onshore wind installations can require substantial space that is not always available in crowded environments, or may compete with other land uses such as agriculture, resulting in population displacements. The most opportune locations for renewable energy technologies may coincide with land that holds cultural or historic significance, including for indigenous communities. Regarding biodiversity, the deployment of renewable energy technologies may also lead to habitat loss and or disruption of migratory patterns. Careful attention, therefore, must be placed on ensuring that the chosen technology options minimise negative side effects while reaching their climate mitigation potential. However, beyond negative impact mitigation, the manner in which energy technologies are deployed can create positive outcomes for local communities and national economies, such as through the provision of local energy access or the creation of job opportunities. If communities and different stakeholders are involved in the decision-making and execution of energy projects, it will create more positive perspectives on the initiative. This guidebook will suggest ways in which nationally endorsed technology measures can be deployed while minimising negative social and environmental impact and maximising social and economic benefits, with a general recommendation that countries consider a holistic approach for the energy transition, balancing climate objectives with socioeconomic priorities (UNFCCC – Decision 1/CMA.5, 2024).

While Just Transition principles transcend types of energy technologies, different aspects of the Just Transition take on greater significance depending on the technology in question. As such, in the assessment of each of the technologies covered in this guidebook, we have included analysis of the key Just Transition issues of relevance.

2.3. Identification of gaps and opportunities

A higher uptake of renewable energy sources in the power sector will inevitably entail a higher reliance on technologies that provide a variable, or intermittent, generation of electricity. This is true for two of the key technologies included in this guidebook, solar PV and wind.

The intermittent nature of these technologies can be compensated with renewables that provide baseload electricity, such as geothermal or hydropower, as well as extensive storage. A thorough decarbonisation of the power system in developing economies will, however, still require too wide an adoption of variable renewables for policymakers to rely exclusively on these

2 In the discussion of Just Transition across energy technologies and energy storage within this publication, the focus is on the deployment of the technology or storage system, rather than its production. There are various Just Transition considerations related to energy technology production, such as the protection of human rights and the environment in the mining and manufacture of technology inputs, but they are beyond the scope of this publication.

backup solutions. In its updated roadmap for net zero by 2050, the IEA specifies that solar PV and wind will amount to 40% of global electricity generation by 2030 (IEA, 2023c). Moreover, changing rain patterns brought by global warming are reducing the reliability of hydroelectric energy in many developing countries seeking to expand the deployment of variable renewable energy solutions.

Other renewable sources will play a crucial role. Biomass, geothermal and marine energy can provide reliable power generation, while hydropower will potentially transform into a frequency regulator and a tool to ramp up power generation through its pumped hydro variety. Careful consideration must be given to not outcompete food crops or replace forested areas by providing the wrong bioenergy incentives, or to avoid over-relying on systems that could be jeopardised by climate change, such as large hydropower stations.

Technologies to improve the demand-side management of grid transmission and distribution system, innovative approaches to the decentralised nature of especially solar PV resources, the deployment of storage technologies also at scale, the inclusion of synthetic inertia and fast-frequency response control as well as green interconnectors, when relevant, are all part of solutions to the challenge of intermittency. New technological advances, such as more efficient solar panels and wind turbines, will also contribute to the solution.

Grid expansion, efficiency and use optimisation

As countries have expanded their renewable electricity generation capacity, a significant challenge has emerged in the form of a gap in investments in transmission and distribution grids, with completed projects around the world still waiting to be connected. This is already a major problem in Europe, where a backlog of grid connection assessments by regulators, as well as grid congestion issues once the plants are finally connected, are keeping hundreds of gigawatt capacity out of the system (WEF, 2024). In developing economies, this issue can be exacerbated by the financial instability of some utilities and regulatory issues, both of which contribute to a lack in investment in transmission and distribution systems.

Moreover, climate change and the need to expand the use of electricity to meet climate goals will necessitate the adoption of new technologies to reduce reliance on generation, and to improve the resilience and efficiency of transmission networks. Dynamic line rating systems, for example, allow operators to change the thermal capacity of transmission cables dynamically, while conservation voltage reduction (CVR) technologies allow utilities to stabilise electricity voltages towards the lower end of an acceptable spectrum, producing energy savings. These technologies, among many others, will be analysed in the section of the publication dedicated to energy transmission and distribution.

Storage

In power grids with a significant proportion of variable renewables, utility-scale batteries with storage durations ranging up to several hours are capable of providing peak power capacity according to necessity – batteries can be charged during periods of high electricity supply, for example, during daytime when generation from solar PV reaches its maximum and then used during high-demand periods, such as in the evening when solar power is no longer available. This function also helps reduce congestion, withholding electricity from the grid when variable renewable energy (VRE) produces extra supply. Large, utility-scale batteries are key for the diffusion of mini-grid systems, which are crucial for the electrification of developing contexts in which large shares of the resident population still live far from the main grid.

Pumped storage is another form of storage based on hydroelectric power and is currently the most widely used form of utility-scale storage in circulation. It consists of managing the flow of water between two levels of altitude, using power in peak production daytimes to pump water onto a higher reservoir and generating electricity in low production times by allowing the water to flow down to the bottom reservoir. They can continue to play an important role, together with battery storage options, to manage the discharge of electricity into the system during low supply, although their reliability has also been put increasingly in doubt by changing weather patterns and more recurring periods of drought.

Increased generating efficiency

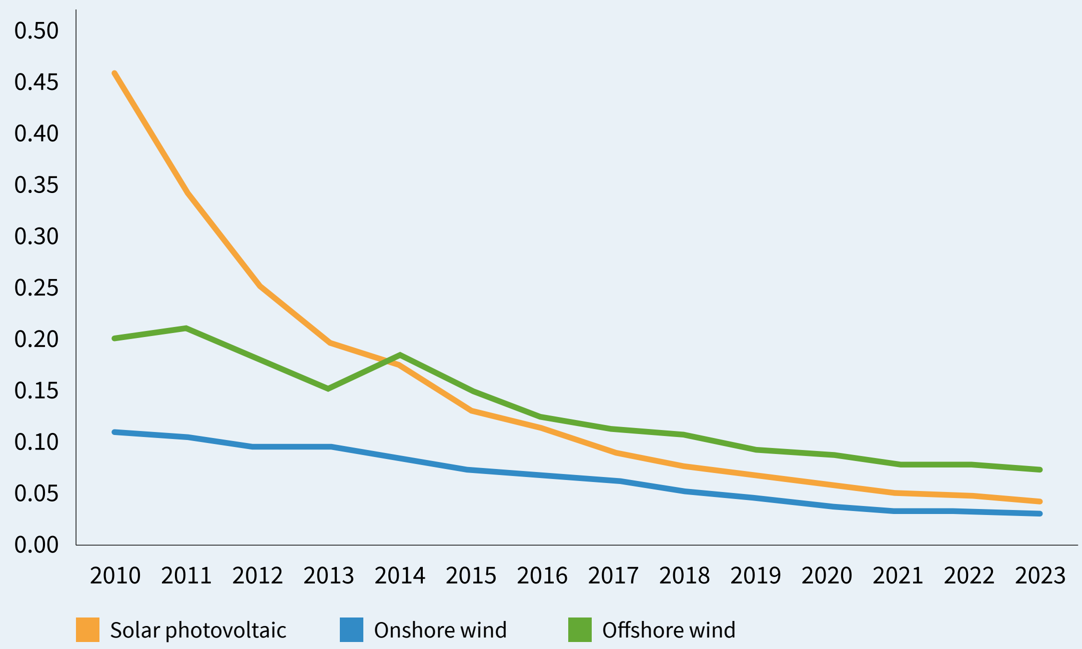
In the past 20 years, huge improvements have been made in the efficiency of equipment such as solar panels and wind turbines. In the future, more technological innovations can further improve their efficiency.

Solar panel prices have seen a dramatic 93% plunge between 2010 and 2020, while costs for large, utility-scale projects have fallen by more than 80% in the same period (Figure 2.2). Simultaneously, new cell structures and architectures have increased the average efficiency of a module from 15% to 20%. This is extremely important, because it allows for a reduction in land use as fewer solar panels generate more and more electricity (IRENA, 2022b).

For solar PV, further advances such as stacked (tandem) solar cells hold promise, together with thin-film modules from non-silicon-based materials, although these are largely dependent on the price volatility of silicon for now (IRENA, 2019b). A particularly interesting material for solar panel production is perovskite, a type of mineral that is particularly apt at absorbing light. While the predominant material currently used for solar panels is silicon, its maximum efficiency has recently peaked at around 27% (The Renewable Energy Institute, 2025). Perovskite, however, shows potential for greater efficiency due to higher solar absorption capability and to its ability to access regions of the solar spectrum that are currently unattainable by silicon. Nonetheless, this technology has not reached market maturity due to problems related to durability.

Just like solar panels, wind turbine installation costs have also declined substantially between 2010 and 2020 (-32%), while average rotor diameter and height increased substantially. Continued improvements such as longer blades, taller towers and in particular wake steering – the possibility of turning the direction of the turbine or modifying the speed of its generator – promise substantial additional productivity gains. In the United States, field trials of wake steering technology in wind turbines allowed for electricity production gains of up to 2% (NREL, 2019).

Figure 2.2: Total average installed costs (2010–2023, 2023 USD/kWh)



Note: Total average installed costs in USD/kWh have dramatically decreased between 2010 and 2023 for solar photovoltaic and both onshore and offshore wind. *Source: IRENA, 2024g*

Substantial potential exists also in bioenergy. Electricity can be generated using multiple sources of bioenergy, some of which are purpose-grown crops that are considered as unsustainable for a variety of reasons (land use, competition with agricultural land, deforestation), and that are best directed to marginal land where no other forms of subsistence crops can grow. Crop residues, waste and leftovers from industrial production are alternative sources of electricity that can be of particular use. New efficiency gains and technological developments will be crucial to ensure that the necessary expansion of bioenergy-derived electricity does not come at the expense of additional agricultural land and forested areas. Some promising developments can be observed in the production of cellulosic ethanol from otherwise discarded feedstocks, or from algae, which would not compete with existing cultivations but rather use waste and residues from these. While ethanol and other biofuels are typically used for transportation, they could play an important role in electricity production especially in more isolated agricultural areas.

New technologies and their development will be explored in greater detail in the core of the guidebook.

2.4. Policies and regulations

Policies and regulatory frameworks play a vital role in ensuring the rapid and smooth deployment of renewable energy technologies. In-depth policy analyses are beyond the scope of this guidebook, but some policy options and considerations are highlighted under individual technologies. Additional sources to consult and detailed studies on renewable energy technology policies (UNEP, TEC and UNIDO) will be presented in Appendix III (Additional Sources of Information on Mitigation Technologies and Practices).

For the sake of a short description in this section, the set of policies available can be split into two categories: regulatory and non-regulatory.

Regulatory policies include quotas/obligations and tradable renewable certificates such as the Renewable Portfolio Standards (USA) or the European Guarantees of Origin scheme (EU), where power generators and electricity distributors accumulate the right quantities of certificates to respect said quotas. Hourly rates can also be used to inventivise consumption towards times of peak electricity production, especially distributed solar – lowering tariffs during the middle of the day, when solar PV reaches its peak, can optimise consumer behaviour and reduce strains on the system when production lowers (such as towards the evening). Feed-in tariffs that guarantee a set off-take price for renewable electricity, as well as guaranteed access to grids and priority dispatch, have traditionally been popular measures to establish a first presence of renewable energy technologies in new contexts, although some concerns may arise over the cost of subsidies. As markets mature and costs drop, large-scale projects can be favoured by auctions where possible developers compete along technical and cost lines, as well as additional criteria such as their impact on communities and on the environment, employment opportunities, and the level of local content used in the development of the project.

Among non-regulatory measures, financial and fiscal incentives can also be used as a tool to facilitate efforts by governments to support the further development of renewables. These can range from tax credits for early stage projects, to concessional loans for developing economies. It is moreover widely acknowledged that delivery models and the operations and maintenance structures when deploying solar PV must include the training of individuals in the community through capacity building efforts. These training activities can extend to operations and maintenance (O&M), performing revenue collection, keeping inventory, relaying with external actors as well as government agencies (IRENA, 2023c). This guidebook will delve into technology-specific policy case studies as we discuss each technology option in greater detail.

3. Mitigation technologies and practices


Photo: pexels | Pok Rie

This chapter provides a definition and description for each technology solution, followed by information such as advantages and disadvantages in technology deployment, economic assessment and affordability, mitigation and net zero emission potential, Just Transition aspects, climate resilience consideration and other characteristics that may be taken into account by national teams when prioritising technologies for climate action.

Moreover, technology measures are accompanied by country examples that showcase successful initiatives, lessons learned, together with insights and good practices from real-world implementations.

The technology solutions that are included in this chapter are:

- Energy supply technologies;
- Energy storage;
- Energy transmission and distribution.

Overall, the guidebook will emphasise the following points:

- It is important for countries to widen their portfolio of preferred technology options, rather than relying exclusively on one single energy source. This increases resilience to price fluctuations, weather and climate events, changing climate conditions, geopolitical fragilities, and other external shocks such as pandemics or social unrest.
- Countries may pursue options of decentralisation of energy sources to maximise resilience.
- Countries may privilege technology options that allow them to maintain self-sufficiency in the face of sudden price spikes or supply chain constraints.
- Countries are encouraged to carefully consider aspects of Just Transition when deploying these technologies, ensuring that these generate net gains in total employment, an improvement in job quality and incomes, and social inclusion, while mitigating potential pitfalls generated by economic restructuring, and shifting employment needs (UNFCCC, 2020).

These principles will allow countries to maintain a balanced approach when transitioning to a greener energy system, maximising their energy security while developing a system that is resilient.

3.1. Energy supply technologies

3.1.1. Solar photovoltaic

Technology definition and description

Solar photovoltaic (Solar PV) is a technology through which sunlight is converted directly into electricity through semiconducting materials that allow electrons interacting with light to flow in a specific direction, creating an electric current.

Solar panels are typically composed of a stack of two silicon layers, which are mixed separately with other elements (boron and phosphorus) allowing for the creation of an electric field between them. On top of the two stacked layers, a layer of anti-reflective coating allows for the absorption of as much sunlight as possible. This is necessary due to the nature of silicon, which is highly reflective.

The two silicon layers are stacked on top of each other, with the top layer containing a mixture of silicon and phosphorus atoms and the bottom layer containing a mixture of silicon and boron atoms. The atomic structure of these materials allows for the creation of a system in which photons from sunlight penetrate the surface of the solar cell, knock floating electrons within the junction between the two silicon layers, and set off a chain reaction in which electrons flow from the top layer of the cell, through a circuit, back to the bottom layer of the cell, generating electricity in the process.

Solar PV has evolved substantially in the last 10 years, both in terms of the materials used to produce the single cells as well as the type of cells being used. This has in turn contributed to vastly increasing average cell and module efficiency rates. Early 2021 estimates compiled by IRENA indicate for example how the commercial efficiency of the most recent cell technologies have now reached close to 24%, from 20-21% just 7 years prior (IRENA, 2022b). Similarly, the average efficiency of solar PV panels has risen from 14.7% in 2014 to 21.4% in 2021 (IRENA, 2024g).

At the same time, inversely to the rising efficiency of solar PV modules, the land they occupy has decreased in terms of hectares per MW_p, from 2.69 hectares in 2010 to 1.94 in 2021 (IRENA, 2022b)

Solar PV is also witnessing the emergence of new technologies that can drastically increase its efficiency:

- **Thin-film Perovskite Solar Panels**: The process to produce silicon crystals is very energy intensive. Alternative methods utilise human-made materials that imitate the crystal structure of perovskite material structures otherwise found in nature. This material is more efficient than silicon and requires less energy in its manufacturing process. It can be combined with silicon layers in hybrid perovskite-silicon cells or used autonomously. Perovskites still, however, face some challenges: they show a propensity to degrade when exposed to humid conditions. This technology is not yet available commercially but should be monitored as a potential technological breakthrough for solar panel material production (IRENA, 2019b).
- **Concentrated Photovoltaics**: This is not so much a different material to produce solar cells, but a system structure that concentrates sunlight onto solar panels using lenses, light collectors or mirrors, which affect the degree of intensity of sunlight concentration. This allows these PV systems to attain extremely high levels of energy efficiency. Because of the high degree of sunlight concentration, these systems require cooling systems that makes them more expensive and so are better used in very large-scale installations (Arif Fikri et al., 2022).
- **Bifacial Modules**: This technology allows solar light to enter the rear side of the cell, as well as the front – these types of cells are usually deployed on a bifacial module, generating a higher yield than traditionally monofacial modules. Moreover, this type of technology can allow for deployment at broader latitudes, expanding the geographical range where solar PV can become a competitive energy source (IRENA, 2019b).

Advantages and disadvantages

Solar PV is one of the most crucial technologies to achieve net zero carbon emissions by 2050 and limit global warming to 1.5°C by 2100. The IEA estimates that more than 6,000 gjgawatt of solar PV capacity will have to be installed worldwide by 2030 for the world to be on track with achieving this objective, a 2.5-fold increase compared to today (IEA, 2023b), and amounting to 80% of the growth in renewable energy capacity.

At the same time, global new solar PV installations amounted to 73% of all new renewable energy projects in 2023, reaching up to 90% in Central America and the Caribbean, and 84% in the Middle East (IRENA, 2024g).

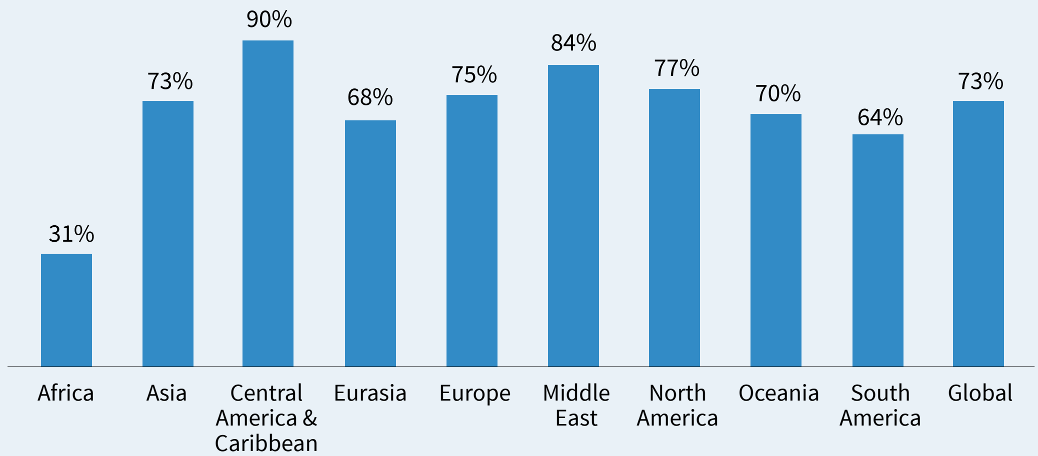
Solar PV is also an essential resource to provide electricity to areas that have not been connected to a national grid. Off-grid solar PV solutions, in particular, will be essential to ensure that many countries in sub-Saharan Africa fulfil their objectives to achieve 100% access to electricity. The technology's modular and distributed nature makes it very adaptable to a wide range of solutions, from utility-scale projects to mini-grids, all the way down to solar home systems in stand-alone form. Moreover, in several countries there might be significant hosting capacity for solar PV within distribution networks that could be taken advantage of without the need of significant new investment in the grid.

Solar PV may however present some drawbacks: first of all, the industry is at the moment highly geographically concentrated (IEA, 2022), and countries wishing to rapidly ramp up the installation of solar PV might want to secure imports from different suppliers, or kick-start their own solar panel manufacturing industries. Utility-scale solar PV also requires a significant amount of space (IRENA, 2021c), which may raise issues in heavily populated areas in countries where agriculture is still an important means of sustenance for local communities, or where new solar PV projects can clash with increasing rates of urbanisation. This issue can be solved potentially with the adoption of agrivoltaics, which involves fixing solar panels a few metres above ground while soil cultivation can take place beneath. Moreover, the intermittent nature of solar PV's electricity output will likely require grid modernisation efforts to increase its flexibility, including investment in storage as well as local capacity-building to accommodate for this effort (IRENA, 2018).

Economic assessment and affordability

In the period between 2010 and 2023, solar PV has experienced one of the most dramatic cost reductions not only when compared with fossil fuel sources, but also among all other renewables. According to IRENA, the global weighted average levelised cost of electricity (LCOE) costs for utility-scale solar PV projects has declined in this period by 90%, largely because of a fall in panel manufacturing costs. In total, global energy savings from avoided fuel imports directly attributable to solar PV amounted to USD 20 billion in 2023, or 43% of total savings from renewables (IRENA, 2024g). If this trend continues, solar PV is predicted to become the most affordable energy source in almost all countries by 2030. (Nijsse et al., 2023). This, together with a rise in capacity factor due to increased module efficiency, has contributed to making solar PV the success story of renewables.

Figure 3.1: New Solar PV installations by region (share of new renewable energy capacity additions)



Source: IRENA, 2024g

Solar PV also presents some cost disadvantages. Figure 3.1 reveals a limited presence of this technology in certain regions, particularly Africa, despite the high adaptability of this resource to achieve full energy access. This is mainly due to solar PV's relatively high capital costs in countries in the region, and the grid flexibility and modernisation requirements that come with such an intermittent source of power.

Installation costs for utility-scale solar PV may vary considerably across countries. In South Africa, they can go up to USD 1,200 per kWh, compared to half the amount in Spain. And while hardware costs, such as for modules or inverters, between these two countries are largely similar, the gap is caused primarily by financing costs and compliance costs to benefit from subsidies (IRENA, 2024g).

A comparison of financing costs surveyed in various countries between 2019 and 2021 reveals large disparities. The weighted average cost of capital[3] in Egypt for utility-scale solar PV projects was 9.7%, in Morocco 9.1%, in South Africa 6.9%, in India 7.1%, in Italy 4.3%, in France 3.4%, in China 3.9%, and in the USA 5.4% (IRENA, 2023e). The disparities between these countries are generated by a multiplicity of factors such as higher perception of risk profiles in developing countries, lack of long-term lending markets, lack of available infrastructure or local capacities and skills, or unclear regulation and incentives (Energy for Growth Hub, 2018).

3 $WACC = K_d \times L \times (1\text{-}T) + K_e \times (1\text{-}L)$
K_d = cost of debt
L = leverage (share of debt)
T = tax rate
K_e = cost of equity

Mitigation and net zero emissions potential

Solar photovoltaics are an inherently 100% clean source of electricity production. The process of manufacturing solar panels, however, is energy intensive. As explained above, silica is melted and purified in electric arc furnaces at very high temperatures and then treated in the following stages to create solar panels. According to this argument, new solar panels are produced with an inherent "emissions debt" that needs to be paid off throughout the years that these panels produce emissions-free electricity.

This issue is, however, becoming increasingly less important. As more and more electricity is produced from non-fossil fuel sources, emissions generated from the high-temperature melting of silica in turn decrease. At the same time, increasing efficiency rates from solar panels have drastically reduced the amount of time it takes for a solar panel's activity to 'pay off' the emissions debt it incurs during its manufacturing process. The result is that life cycle emissions from solar PV, while still there, are 12 times smaller than natural gas, now considered as the most emissions-friendly fossil-fuel source for producing electricity (Figure 2.1).

Solar panel decommissioning and recycling practices are also improving – estimates currently point to 85% of the materials used in a solar panel being recyclable (US Department of Energy, 2024a), and improvements in recycling processes could push this threshold even higher. This will be an increasingly important issue as more and more solar panels are manufactured to support the energy transition.

Just Transition aspects

There are various concerns and opportunities related to a just energy transition that policymakers should consider when developing solar energy projects. For example, sites must be selected appropriately to avoid disturbance of indigenous land, cultural and religious sites, or other sites that contribute to the livelihood of local communities. Solar development must respect and uphold indigenous land rights, ensuring that projects are not imposed on indigenous or local communities without prior and informed consent. National strategic environmental social assessments (SESAs), and other similar tools at the disposal of governments and international organisations, can be useful to map solar potential against any biodiversity risks, such as impacts on herding patterns, or socioeconomic considerations, such as competing land use with agriculture. Through such assessments, land with the lowest risks of negative social and environmental impact should be prioritised. Solar plants require large swathes of land and can use significant amounts of water for cleaning. Efforts to ensure these projects do not conflict with local community's land for food production and water availability can avoid or mitigate these risks.

Negative social impacts should be mitigated by involving local communities, including indigenous peoples, from the planning phase at the start of the project. Stakeholders, such as project developers and local governments, should not only work to minimise negative social impacts, but they must proactively maximise positive social impacts, assessing the specific needs of the local community, and co-creating projects that lead to net benefits for the local population. These considerations should be included throughout the life cycle of the project, including extraction of raw materials, manufacturing, construction, operation and decommissioning. Governments should design policies that facilitate access to affordable solar-generated electricity, prioritise local job creation, and reinvest revenue from solar projects into community development initiatives such as infrastructure improvements, educational programmes and social services.

Solar energy projects typically generate the most jobs out of all renewable energy technologies. Most jobs are related to the engineering, procurement and construction (EPC) aspects of the project, as well as to its operation and maintenance (IRENA 2024f). This presents multiple areas where local jobs can be created. In preparation, project developers and relevant stakeholders can create partnerships with local academic and professional institutions to offer training opportunities and equip members of the local community with the skills that will be in demand during the project lifetime. This should include retraining opportunities for workers whose jobs may be at risk due to the energy transition. Training opportunities should also look to empower women, who globally already account for 40% of the solar energy workforce, and which can help them find employment and earn an income (IRENA, 2024f). However, informal and precarious employment in the solar industry, particularly in installation and maintenance roles, raises the need to ensure fair wages, job security and access to benefits.

Enhancing climate resilience of energy technologies

Climate change has the potential to impact solar PV performance in a number of ways (IPCC, 2022):

- Increased temperature extremes, as well as increased weather variability, can affect the performance of solar PV cells, sometimes even causing irreparable damage. These damages can be caused by an increase in mean air temperature as well as by a higher recurrence of heat waves.
- A higher incidence of wildfire smoke and ashes, as well as an increase in the size of wildfires, can impact solar PV production through ash sedimentation or by blocking sunlight.
- More extreme storms can damage infrastructure, particularly affecting improperly attached solar panels.
- Droughts may reduce water availability for cleaning the modules.

The measures that can counter these future effects can vary from more resilient solar panel designs incorporating climate models when installing solar farms and conducting site-specific assessments, as well as panels that are compatible with dry cleaning technologies.

Barriers to dissemination / deployment

Solar PV may face a series of barriers to its deployment, especially in countries that can be categorised as developing economies.

Grid flexibility: Solar PV is a technology that depends on an intermittent source of energy. This requires a sufficiently flexible grid system coupled with reliable storage infrastructure. A grid system that is unprepared to integrate electricity from intermittent energy sources can face curtailment and other operational issues. There are available options to deal with the variability of this resource, which include enhancing the flexibility of supply via providing for more stable renewable energy resources such as hydro and geothermal, facilitating flexibility from the demand side through targeted pricing mechanisms, strengthening interconnections with other areas and other regions (IRENA, 2018), and integrating solar with storage options as well as technologies that modernise the transmission and distribution grids (see relevant sections).

Land and water use issues: Solar photovoltaics at utility scale may occupy vast areas of land. The land requirements are falling due to increasing levels of efficiency and can also be offset by floating solar PV deployment. In the short term, however, this can still pose a problem especially in countries where more land is used for agricultural purposes. At the same time, substantial amounts of water are needed to clean solar panels so that they can harness the highest amount of energy from sunlight. Estimates have shown that this could amount to 3.8 litres of water per MWh, which would be a far smaller amount than what would be required by electricity generation from natural gas (10.6 litres of water per MWh) (US Department of Energy, 2023). Dry cleaning solutions such as robotic panel cleaning technologies, however, have recently become more widespread and can help alleviate issues related to water use. They entail a substantial CAPEX investment, but they are very well suited to areas prone to soiling and with little water availability, being deployed especially across the Middle East and North Africa.

Investment barriers: Several types of barriers are still hindering investments in solar PV. Problems vary between scepticism on the adequacy of the grid infrastructure, complicated processes to obtain necessary licensing and permits, lack of infrastructure and financial instability of off-takers, as well as the structure of power purchase agreements, which favour long-term contracts between the off-taker and the power producer that is sometimes not preferred by risk-adverse actors. A study conducted in nine Asian countries (EY, 2023) highlighted potential measures for overcoming financing issues in solar PV, including: blending domestic and international financing, recurring to credit guarantees, establishing local green bond markets, using subsidies and tax incentives to attract private investments, and developing standard model power purchase agreements.

Solutions in the real world

Agrivoltaics in Kenya and Tanzania

Two of the main issues related to the application of solar PV are the takeover of extensive tracts of land that could be used for growing crops, and the use of water to cool down, and clean, the solar panels to maintain their efficiency. In Kenya, one solar PV farm has sought to address these issues. In Insinya, southern Kenya, a 62kW solar PV system arranges panels in grids of three and elevates them 3 metres above ground, instead of keeping them close to the ground as is usually done (World Economic Forum, 2022a). The shade provided by these panels creates an ideal microclimate for the growth of certain crops, while guttering systems on the lower frame of the panels collect rainwater into storage tanks to be utilised for their maintenance and for the irrigation of crops. According to a research study on agrivoltaics in Kenya and in Tanzania, crop survival rates during warm periods improved under the shade of the solar panels (Randle-Boggis et al., 2025).

In Mali's Bougoula village, a hybrid solar mini-grid facility has been installed to provide clean electricity to more than 30 villages in the area. This system facilitates agricultural activities, powering water pumping for irrigation and other agricultural machinery, which leads in turn to increased crop yields and economic opportunities for the families in the community. The electricity generated has also improved the performance of local healthcare providers, lengthening medicine preservation by providing the power to run refrigerators in the local pharmacy. Decentralised renewable energy solutions, very often powered with solar PV, are a central aspect of Mali's electrification strategy, which plans to phase out diesel-generated systems in favour of mini-grids running on solar PV (IRENA, 2022c).

3.1.2 Wind energy

Technology definition and description

Wind power is a technology by which wind is converted into electricity through a mechanical process.

Wind power turns the blades on a rotor roughly 10–20 times per minute – a series of gears connecting the rotor shaft to the generator shaft will multiply the revolutions of the latter by roughly 75 times, allowing for the very fast rotation that is necessary to power a turbine.

This system of gearboxes is susceptible to wear and tear, requiring repairs after an average period of seven years. Moreover, lubricants coating the gears can leak onto the soil and these systems can also generate noise contamination. Some wind turbines have therefore eliminated the gearbox structure and begun to resort to larger-diameter generators, which compensate for slower revolutions and maintain sufficient output frequency.

Direct-drive systems are likely to become more widespread in the future, especially as advances in technology increase turbine size and capacity. This will likely increase the demand for rare earth materials used for generator magnets, making the manufacturing of wind turbines with very large generators susceptible to price fluctuations for these materials.

Generating electricity from wind turbines is currently possible from both onshore and offshore facilities (see Table 1). Both technologies have witnessed dramatic cost declines as well as increases in capacity factors, while respective weighted capacity factors have in the meantime increased to 36% for onshore and 45% for offshore (IRENA, 2024g).

Table 1: Costs for wind technologies

	Onshore wind	Offshore wind (fixed)	Offshore wind (floating)
LCOE	USD 0.033/kWh	USD 0.075/kWh	USD 0.2/kWh
Average installed costs	USD 1160/kW	USD 2800/kW	USD 5975/kW
Weighted capacity factors	36%	45%	NA

Source: IRENA, 2024g

While onshore wind systems are cheaper and easier to maintain, offshore wind technologies provide a greater and more consistent electricity output, and their components are generally easier to transport, via boat, to the installation site. The technical feasibility and type of offshore wind depends, however, on a series of parameters, as ranked by an Energy Sector Management Assistance Program (ESMAP) analysis (World Bank, 2019) for offshore wind technical potential: regions with annual average 100-metre height wind speeds of greater than 7 metres/second are considered technically viable. For depths of less than 50 metres, fixed offshore wind platforms are advisable, where the turbine is anchored to the bottom layer of the ocean. For depths ranging from 50 to 1,000 metres, floating farms are recommended.

Floating offshore wind is set to become an increasingly promising technology (IRENA, 2024b). It allows countries that deal with space issues and are enticed by the greater electricity output from offshore wind facilities to install these technologies at a greater distance from the coast, where the winds are stronger. The technology is particularly appealing for countries whose territorial waters are characterised by a steep drop in seabed depths. Floating offshore is underpinned by several technological components:

- a floating foundation that anchors turbines to the bottom of the seabed, and that simultaneously maintains stability against currents and rotation inertia;
- specialised turbines with minor modifications;
- a mooring system;
- a robust power system to connect the turbines to an onshore site – these cables are specifically designed to withstand currents and for exposure to saltwater.

Advantages and disadvantages

Wind energy is a clean source of power. Similarly, wind turbines emit life cycle emissions largely from their manufacturing and disposal process, although at even lower levels, particularly for onshore technologies (see Figure 2.1).

Wind energy is also an intermittent source of electricity, requiring extensive storage capacity when the wind does not blow, and a similar effort in increasing grid flexibility to integrate electricity from variable energy sources.

Wind energy exhibits, however, different seasonal patterns from solar PV; solar and wind complementarity can help manage the grid and reduce the need for storage options (Solomon et al., 2020). Offshore wind farms in particular exhibit inherent seasonal characteristics that partly explain the recent enthusiasm for expanding this specific type of capacity, even if it is more expensive compared to onshore wind. Offshore wind tends to blow stronger at night, when onshore wind speeds abate, and the sun does not shine. This means that in a future that will depend exclusively on renewable energy, offshore wind can provide a source of electricity at times when other complementary sources do not, and potentially cheaper than onshore battery storage solutions.

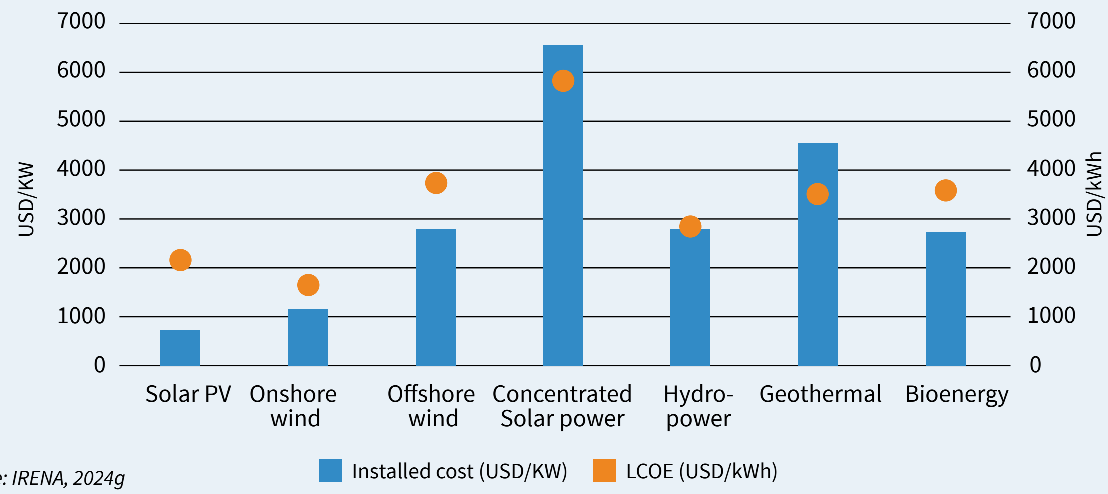
Onshore wind farms can however raise concerns regarding the extensive amount of space they may require. Displacement of bird and terrestrial animal species may also occur. An appropriate siting of bird or bat migration routes when deploying wind farms can help mitigate this issue (Tolvanen et al., 2023), as well as accurately conducted environmental assessment studies before the start of a project. Offshore wind solutions, at the same time, can occupy more space and, if placed far enough from the shore, and can help resolve visibility issues that cause some opposition to new wind farms.

Compared with onshore wind, offshore wind farms are more expensive to install, maintain and repair. The highly corrosive nature of the environment they are situated in, full of salt particles, make them susceptible to rust. Repair operations may be more complicated due to the need to transport technicians on site via boats, and probably via helicopter. Moreover, installing offshore wind farms in high-depth marine environments requires a level of technical expertise that can lead to higher costs when compared with smaller-sized onshore wind farms.

Economic assessment and affordability

Like other sources of renewable energy, especially solar PV, both onshore and offshore wind have seen their costs decline dramatically from 2010 to 2023. LCOE has declined by 70% for onshore and 63% for offshore, and onshore wind currently presents the lowest LCOE cost per kWh out of every other mature renewable energy source.

Figure 3.2: LCOE and average installed costs for renewable energy



Source: IRENA, 2024g

Compared to solar PV, however, wind energy presents higher upfront costs (Figure 3.2), especially offshore wind, due to the challenging environment in which installation must take place. Floating farms especially can be situated in areas reaching very high depths, kilometres away from the shore. The difficulty these environments present also increases operational and maintenance costs.

Just as with solar PV, wind energy presents differences in the cost of capital between projects financed in more developed economies and those situated in more fragile settings. A comparable review of average weighted cost of capital for projects around the world has yielded somewhat similar results, with the weighted average cost of capital for onshore wind in countries such as Kenya and South Africa (7.2 and 7.5% respectively) being much higher than in countries such as China, France (both 3%) and Germany (2.4%) in the period from 2019 to 2021 (IRENA, 2023e).

Finally, it is important to note that an increased global market fragmentation and heightened geopolitical tensions could create bottlenecks in the provision of rare earth minerals for the production of turbine generator magnets, which could increase costs for wind turbines in the future.

Mitigation and net zero emission potential

As explained above, wind energy presents the highest mitigation potential among all renewable energy sources. In addition to being a completely clean form of producing electricity, the life cycle emissions for both onshore and offshore farms are merely 12 and 11 gCO_2eq/kWh. Carbon payback periods for wind turbines are consequently shorter than for solar panels, averaging from a few months at best to a couple of years for most farms. These fall well below the average lifespan of a wind turbine (25 years), which is the minimum payback period threshold required to achieve net zero emissions from any technology.

Still, even this relatively minuscule carbon footprint can be further reduced via electrification of turbine manufacturing processes as well as those for rare earth mineral extraction and processing.

Just Transition aspects

Just Transition considerations for wind energy projects, especially those for onshore installations, include similar aspects compared to solar energy. This includes conducting environmental and social assessments, prioritising areas that have a low risk in terms of impacts, providing free and transparent information about the project, and ensuring fair compensation for local populations who consent to relocate.

Open opportunities for dialogue and negotiation are needed to ensure that the needs of local communities, including indigenous, women, minority groups and disadvantaged members of the community, inform the planning and implementation processes. This is especially important as areas suitable for onshore wind energy installations are typically in rural or indigenous lands. Changes to the landscape and built infrastructure may disrupt cultural traditions and preferences from indigenous peoples. Thorough cultural sensitivity consultations and ideation around collective benefits are essential. Depending on whether the land is leased or purchased, onshore wind energy projects can guarantee a predictable regular payment or a significant lump-sum payment for landowners. For this, landowners and community members should receive sufficient information, as well as financial and legal advice, to ensure fair agreements. Consideration may also be given to how offshore wind technologies may impact indigenous communities and/or coastal communities, regarding areas where they may have traditionally fished, hunted or gathered marine resources.

Wind energy projects – both onshore and offshore – can provide employment opportunities in decent jobs with fair wages, benefits and safe working conditions, for example, in manufacturing, installation, operation and maintenance. For instance, offshore wind projects offer direct and indirect employment opportunities in related industries such as shipbuilding, port services and marine logistics. Conducive labour market policies that facilitate local hiring, retraining and skills certification are among measures that could promote a Just Transition and provide support to workers in industries that may be negatively impacted by the shift to wind energy.

Wind energy is a key enabler of the energy transition, providing affordable electricity without generating GHG emissions. However, wind installations can have undesired impacts on wildlife and the environment. During the site identification phase of a wind energy project, potential impacts to birds and bats need to be studied and well understood. This includes a variety of methods like field surveys, satellite monitoring, and models for predicting bird routes and locations. Avoiding locations with high populations of birds, migration routes, and nesting sites can reduce potential impacts and bird collisions with wind turbines. These impacts can be disproportionally high for vulnerable species like eagles, storks, and vultures. The impacts need to be understood not only from the perspective of one wind turbine or one wind farm, but rather from different installations across the path of migration birds, which result in cumulative impacts. Harm to bat populations are even higher than those of birds and mammals, as they are attracted to the structure of the turbine rotors. Considering this and bats' slow reproductive rates, innovative efforts to minimise such hazards are needed. Land fragmentation from roads and electrical grid infrastructure can also have severe impacts on biodiversity. Careful site selection of wind turbines and their supporting infrastructure is crucial, stakeholder engagement including benefit-sharing, and mitigating as well as offsetting negative environmental impacts are important components that should be accounted for just and fair wind energy project.

Enhancing climate resilience of energy technologies

Changing weather patterns from global warming are expected to impact wind power potential in the following ways (IPCC, 2022):

- Wind 'droughts' affecting large geographical areas, brought about by rising mean temperatures. This is manifested in lower wind speeds in certain areas.
- Increased mean air temperatures decreasing air density and reducing wind farm productivity.
- Increased and more intense storms affecting wind farm infrastructure, together with heavier hail and snowfall.
- Increased mean air temperatures damaging the performance of turbine equipment.
- Relative sea levels that can impact the performance of offshore wind farms.

These phenomena can be countered through a series of measures (Gonçalves et al., 2024):

- Manufacturing turbines and turbine components with greater resilience to higher air temperatures by using advanced materials and coatings to protect sensitive components, by upgrading cooling and ventilation systems, and by optimising turbine designs to account for potential reductions in wind speeds. Countries should source the most advanced models available and ensure that they are up to date to confront the potential climate risks described above.
- Strengthening wind farm infrastructure against extreme weather events, by improving protection against hail and snowfall through hail-resistant blade coating or active blade heating and anti-icing systems.
- Adapting offshore wind farms to rising sea levels by elevating turbine foundations or adapting floating farms in deep waters with special counterweight and pulley systems to better respond to waves,

strengthening anchoring and foundation systems, or implementing adaptive maintenance strategies.

- Planning electricity outputs and projected changes in wind speed when developing wind farms, via the integration of climate models into wind resource assessments, enhancing forecasting abilities through the installation of sensors, and by diversifying wind farm locations to reduce the risk of wind droughts.

Barriers to dissemination / deployment

Wind power will be an important technology to reach net zero emissions by 2050. In the period between 2017 and 2022, it accounted for the second-highest volume of renewable capacity additions, after solar PV (IEA, 2024e). Most of these new capacity additions came from onshore, but offshore is in an initial stage of expansion and will play an increasingly important role as costs come down and technologies advance. According to the IEA, a net zero emissions scenario by 2050 sees wind power generation capacity reach second place out of all other sources including fossil fuels (IEA, 2023b). However, some relevant barriers to deployment still exist today, many of which are also found in solar PV technologies.

Intermittency of power source: Like solar PV, wind is an intermittent energy source, although it is more consistent when installed offshore. A substantial deployment of wind power will require efforts in grid modernisation to increase its flexibility, and a deployment of storage options.

Cost trends: Like solar PV, wind turbines have experienced a decline in costs in recent years. Some analysts, however, foresee potential cost rises in the future, due to a number of reasons (World Economic Forum, 2023): the increasing size of turbine blades and tower heights is already straining supply chains along several crucial chokepoints such as appropriately sized vessels to transport blades that reach the length of a football pitch will be increasingly important as floating offshore facilities take off. Similarly, an increasing demand on the critical minerals required for ever-larger quantities of generator magnets will exert pressure on their supply chains, which are already heavily concentrated. This phenomenon could intensify as wind farms shift from gearbox systems to direct-drive systems requiring ever-larger generators.

Permitting and financing costs: Wind energy already presents higher upfront costs than solar PV. The cost dynamics described above could widen this gap even further, raising financing costs and exacerbating the weighted average cost of capital (WACC) gap between developed and developing economies. Pooling resources by private sector developers, in conjunction with public-sector partnerships, could help alleviate the issue – offshore wind 'islands' are already being developed in the North Sea, with different private sector developers contributing to the development of the site (IRENA, 2021b). Streamlining administrative processes through one-stop permitting agencies can also accelerate wind energy deployment (IEA, 2023a) and solve some backlog issues (World Economic Forum, 2024b), as demonstrated by Denmark's efficient permitting framework, which reduces approval times to approximately one year.

Solutions in the real world

The Cabeolica wind farm, established in 2009 and operational since September 2011, marked a significant step in Cabo Verde's transition towards renewable energy (IRENA, 2025). The system supplies electricity to the grids of several islands, and has played a key role in reducing dependence on fossil fuels and mitigating power shortages while lowering fuel costs.

Beyond energy production, the government has emphasised social and environmental responsibility, ensuring that wind energy development aligns with local needs. For instance, after the construction of the wind farm, agreements were made to allow small farmers to continue grazing their cattle under regulated safety conditions. Since 2013, environmental education programmes in schools have been introduced to raise awareness about renewable energy and conservation, particularly focusing on protecting bird species on Boa Vista.

The wind power infrastructure, initially introducing 25.5 MW of capacity across four islands, has contributed to 25% of the country's electricity supply. Recent approvals have paved the way for further expansion of wind capacity and the addition of energy storage infrastructure. These investments aim to stabilise the grid, store surplus renewable energy and reduce reliance on costly fuel imports, and are in line with Cabo Verde's willingness to further diversify its energy mix, providing a benchmark example of how small island nations can benefit from renewables (IRENA, 2024a). By increasing the share of renewables in the energy mix from 20% to 30% by 2025, the country expects to save EUR 1 million annually on fuel imports, demonstrating its strategic approach to achieving energy security and sustainability (IRENA, 2025).

3.1.3. Hydropower

Technology definition and description

Hydropower is a mature energy technology that generates clean electricity through the mechanical process of water flowing through a dam and spinning a turbine. Most typically, the water is accumulated inside an artificial basin created by erecting a dam. Other types of hydropower facilities are 'run-of-river', which means they use the current of water flowing downstream to spin a turbine and generate electricity. This process entails diverting part, or the entirety, of a course of water into a powerhouse, then feeding the water back into the river further downstream.

Hydropower projects can also be subdivided into 'large scale' (usually well over 100 MW) and 'small scale' (usually less than 10 MW. Small-scale projects are often used for smaller-scale communities and mainly for energy access purposes, or to power smaller industrial activities. They are often used in conjunction with a mini-grid. IRENA estimates that the number of people connected to hydropower-based mini-grids has increased from 5.7 million in 2012 to 7.2 million in 2021, mainly in Asia (IRENA, 2023b).

Another form of hydroelectric system is pumped storage, which is a system connecting two basins at different levels of altitude. This type of technology releases water from the top basin into the lower one during times of peak electricity demand and pumps the water into the higher-altitude basin during peak supply. This acts as a very efficient form of storage that can be complementary to large-scale lithium-ion battery systems and concentrated solar power (CSP) plants, and places this form of storage among the topmost efficient[4].

Hydropower's role within a renewables-based electricity system is to provide a source of balancing and frequency regulation to the grid. This means that because of the ease with which generator frequency can be controlled and manipulated, when compared with intermittent sources like solar PV and wind, hydropower can rapidly bridge gaps between electricity supply and demand.

All types of hydropower described above provide this service to a certain extent, with pumped hydro being the best suited technology type and run-of-river systems the worst.

The IEA estimates that a large share (40%) of the existing hydropower infrastructure is very old, reaching at least 40 years of age following a spurt of installations from the 1960s to the 1980s (IEA, 2024f). This means that the system is in urgent need of refurbishment, especially in the face of an electricity system relying ever more on intermittent energy sources. Refurbishment and modernisation efforts will have to focus on renewing equipment, such as variable-speed turbines and new generators, as well as digitalisation to increase plant flexibility and allow for distance monitoring.

In a past environment in which electricity supply could be regulated more effectively, and in which fossil fuel resources dominated electricity production, hydropower functioned mainly as a source of baseload. The steady increase in solar and wind has modified this scenario, with hydroelectric systems being used more and more as peaking capacity. This has accelerated the wear and tear of turbines and other components. New technological innovations in digitalisation and equipment flexibility can however help hydropower tackle these new challenges.

Hybridising hydropower and intermittent renewables is a potential solution to solve the wear and tear problem: pumped storage solutions operate together with solar PV or wind, using the same space and thereby limiting issues related to land acquisition and repurposing. Solar PV or wind would produce electricity at peak hours, while hydropower would provide peak support when necessary (IRENA, 2023d). This combination indicates a potential way forward for hydropower, where its role would gradually shift to an effective form of energy storage, just like large CSP plants, to support an ever-larger share of new variable electricity from solar PV and wind (US Department of Energy, 2024b).

Advantages and disadvantages

As discussed already, hydropower is a source of clean electricity and acts as a source of balancing and frequency regulation to the grid, acting as a backup for intermittent renewable energy sources such as solar PV and wind. Moreover, hydroelectric dams can

4 Energy storage efficiency is determined by how quickly it responds to changes in demand, its capacity to store energy, the rate of energy losses in the storage process and how easily it can be recharged.

provide important ancillary services, such as working as a source for irrigation and other industrial activity requiring water in its production phases.

Small-scale hydropower comes with a few added advantages – its components can often be sourced locally, as can the workforce to set up its infrastructure. Small hydro can thus provide tangible benefits in terms of employment and local value added, often in ways that large-scale hydro fails to provide.

The technology presents some challenges:

- It is relatively high in upfront costs, especially when compared to solar PV and onshore wind (but not offshore wind, see Figure 3.2). Hydropower systems are complex engineering projects that often require large infrastructure and may be difficult to build and finance (IRENA, 2024g).
- These systems exert substantial impact on local ecosystems, which may threaten the survival of local species, alter the livelihood of fish populations, displace population settlements and potentially flood sites of cultural and historical significance (IRENA, 2023d). Approving and proceeding to develop a hydropower project requires extensive and detailed feasibility studies that can slow the process very significantly.
- Hydroelectric projects, especially if large scale, can become the source of significant geopolitical tensions between a country developing a project and a country located downstream from it. Altering the water flow of rivers with hydroelectric dams could substantially impact the livelihoods of communities living downstream and using the water for irrigation purposes (IRENA, 2024c).
- Hydropower is reliant on the hydrology of the site it occupies, and on rain patterns that have become more unpredictable and less consistent due to the impacts of climate change. Prolonged droughts in a number of countries in recent years have jeopardised electricity production and demonstrated how intractable this problem may become in the future (IRENA, 2024g).

Economic assessment and affordability

While solar PV and wind witnessed a fall in their LCOE and installed costs in the period from 2010 to 2023, hydropower (large hydro in particular) experienced an upward trend. In 2023, LCOE were 33% higher than in 2010, and installed costs 92% (IRENA, 2024g). This rise was likely due to the specific locations chosen for the project development, which might have been situated in more challenging geographies, as well as potential supply chain restraints. The development of hydroelectric projects is very capital intensive and requires extensive works for the preparation of the site, infrastructure development, connection to the grid, and ancillary civil engineering works such as tunnels, canals, etc. All this leads to project lead times of up to 10 years, often susceptible to price changes along the supply chain.

While detailed analyses of weighted costs for small hydro are not as readily available, total cost volumes are clearly inferior due to the difference in scale (IRENA, 2024g). Moreover, while small hydro still presents relatively high upfront costs, the composition of such cost structures is quite different, with civil costs for infrastructure amounting to more than half of total installed costs for large-scale projects, and mechanical-electrical equipment costs being the majority share of costs for small-scale projects (IRENA, 2024g). This picture can, however, change according to the project type – small-scale run-of-river plants located on complicated terrains can see their civil costs skyrocket.

Mitigation and net zero emission potential

Hydropower, like all renewable energy sources, is not entirely emissions free. The GHG emissions that are emitted from hydropower throughout their life cycle arise from the construction and manufacturing of infrastructure and components, but mainly and even more subtly from decomposing matter at the bottom of the reservoir, which disperses methane into the water. This methane is then released into the atmosphere as the water flows through the turbine.

Nevertheless, hydropower remains one of the cleanest sources of renewable energy even when accounting for indirect emissions. The IPCC estimates that a median of 24 gCO_2eq/kWh are emitted by a hydropower project within its life cycle (see Figure 2.1), with the bulk of emissions being released within its first 10 to 20 years (IHA, 2025). The only other renewable energy technology that has lower emissions within its life cycle is wind (Figure 2.1).

Even this relatively tiny number of emissions can be reduced via various methodologies: drawing water from closer to the surface, or managing the reservoir to avoid shallower areas, which is where emissions tend to build up.

In any case, hydropower will be essential to achieve the tripling of renewable energy capacity as agreed in COP28. The IEA estimates that this would require a tripling of annual additions in 2029 and 2030 compared to 2027 and 2028 (IEA, 2023b).

Just Transition aspects

Out of all renewable energy technologies, hydropower generates the most energy globally (IEA, 2024f). Hydropower plants not only provide emission-free electricity and crucial energy services that allow the integration of intermittent technologies, such as wind and solar, but they can deliver multiple socioeconomic benefits. Hydropower reservoirs primarily serve to produce energy, but it is estimated that 40% of them provide key social services related to irrigation, fishing, flood control, water supply, recreational activities, among others (World Bank, 2024). Tax revenues from the power plant can make considerable contributions to local government budgets. These should be allocated to social programmes and infrastructure projects that benefit the local community. Revenue-sharing mechanisms should also be promoted so that local communities benefit financially from the project. The development, operation and maintenance of hydropower plants can create many job opportunities. Governments should seek proactive inclusion of local companies to support the products and services required throughout the project lifetime. Similarly, the presence of hydropower plants, offers affordable and reliable energy access, which may also attract companies and lead to the creation of additional jobs. Hydropower projects present an opportunity to not only provide benefits to the local population, but to catalyse social change by creating educational and training programmes for women and socially disadvantaged groups to enter the workforce.

While there are many meaningful benefits associated with hydropower projects that can be maximised, there are also risks that require careful planning and consideration. For example, hydropower plants, along with the roads and infrastructure surrounding it, require significant amounts of land, which may lead to large numbers of people having to relocate from their homes or agricultural land from which they derive their income. To avoid historical injustices, land rights, including those claimed by indigenous communities, should be respected and compensated fairly. Other ways in which the local population's livelihoods may be affected, is through the noise, air and water pollution typically associated with the construction process. Submerging land also heightens the risk of social erosion and landslides on the edges of the hydropower reservoir. These risks need to be carefully studied and communities in risk areas should be informed transparently and compensated if they need to relocate from a risk zone. Another risk resulting from the reservoir is the potential increase from mosquitos carrying diseases such as malaria and schistosomiasis (Ndayiragije and Nkunzimana, 2024). Among other environmental impacts, the dam reservoir can also lead to contaminated water from excess nutrients and algae, as well as changes in temperature that can all affect aquatic life downstream. To ensure a Just Transition, hydropower development must integrate strong social protection policies, enforce environmental safeguards and actively engage local communities in decision-making. Only by balancing economic benefits with social and cultural responsibility can hydropower contribute to a truly sustainable and inclusive energy future.

Enhancing climate resilience of energy technologies

The potentially negative effects of climate change on hydropower production are well known and are mainly brought about by changing precipitation patterns and higher average air temperatures increasing surface water evaporations (IPCC, 2022). The measures that have been studied to counter these effects include the following (IEA, 2020):

- Enhancing reservoir capacity, increasing dam height, modifying turbine types to account for changing water flow rates, by:
  - Increasing the storage capacity of reservoirs to compensate for seasonal and long-term variations in water availability, ensuring a more stable power supply even during periods of drought.
  - Raising dam heights allows for greater water retention, extending operational periods during dry seasons and maximising energy generation potential.
  - Upgrading turbines to accommodate changing water flow rates can improve efficiency under variable conditions. For instance, variable-speed turbines or Kaplan turbines, which operate efficiently under a wide range of flow rates, can help hydropower plants adapt to fluctuating water levels.
- Hardening and redesigning infrastructure to account for severe storms or floods that can damage equipment and power stations, or relocating power stations on higher grounds, by:
  - Strengthening infrastructure through reinforced construction materials, flood-resistant designs and advanced monitoring systems can mitigate risks.
  - Relocating key components of hydropower plants, such as control rooms and substations, to higher elevations can reduce vulnerability to flooding.
- Implementing early warning systems and real-time monitoring technologies can enhance preparedness and response to extreme weather, minimising operational disruptions.
- Building smaller dams upstream, and manage catchments, by:
  - Constructing smaller, strategically placed dams upstream can help regulate water flow and reduce the impact of extreme precipitation events. These dams act as buffer zones, preventing sudden surges of water that could otherwise overwhelm main hydropower facilities.
  - Devising reforestation, soil conservation and watershed protection measures to enhance natural water retention and reduce sedimentation in reservoirs. Proper land-use planning in upstream areas can also minimise erosion and maintain water quality, ensuring long-term hydropower viability.
  - Integrating nature-based solutions, such as wetland restoration and sustainable land management, can further enhance hydrological stability and climate resilience.
- Hybridising hydropower with solar PV to reduce water evaporation, by:
  - Installing floating solar PV panels on hydropower reservoirs to enhance efficiency in multiple ways.
  - Integrating pumped storage hydropower (PSH), which can store excess solar energy by pumping water to an elevated reservoir for later use.
- Improving water flow management using Artificial Intelligence (AI) and satellite monitoring.

Barriers to dissemination / deployment

Hydropower is a site-specific technology. For this reason, components need to be adapted specifically to the morphology and geography of the area of interest, more so than for other renewable energy sources. This makes standardisation more difficult and can lead to increased costsdown the line, due to the difficulty of estimating soil conditions. This may cause difficulties to arise later in the development process (IRENA, 2023d).

Hydropower, like other renewable energy sources, suffers from a lack of financing sources in developing countries. This is because such projects require longer-term loans, with financing institutions preferring to finance loans that can be repaid earlier. At the same time, the process of obtaining permits for hydroelectric projects can be complicated, more so than for solar PV or wind. All of this can cause significant delays in project development.

Finally, the need for more accurate assessment and feasibility studies, also environmental and social impact, adds a further level of complexity to the development of such projects. This is, however, an indispensable step that can reap enormous benefits down the line. A well-developed, sustainable hydropower project can provide large quantities of clean electricity to the local community and region, and provide much-needed flexibility to a fledgling grid system planning to integrate ever more renewable energy.

Solutions in the real world

Nepal's electricity generation is almost entirely powered by hydropower, which supplies nearly 70% of the country's total energy needs (IRENA, 2023c). A vast network of over 3,000 micro-hydropower mini-grids plays a crucial role in providing electricity to off-grid communities, demonstrating a unique model of rural electrification. These small-scale hydro plants, ranging from 5 kW to 500 kW, have been largely owned, constructed and managed by local communities, with technical and financial support from the Government of Nepal, international NGOs and development partners. Since their introduction nearly 50 years ago, micro-hydro projects have transformed rural energy access, creating economic opportunities, supporting local livelihoods and enabling electrification of households, telecom towers and commercial enterprises. The success of Nepal's decentralised hydropower sector is deeply tied to the existence of two pioneering vocational institutions: the Butwal Technical Institute (BTI) and Balaju Yantra Shala (BYS) in Kathmandu (IRENA, 2023b). These centres, established with European technical cooperation in the 1960s, were instrumental in developing Nepal's homegrown small-scale hydropower sector, manufacturing turbines and training the workforce needed to build and maintain distributed generation capacity.

While micro-hydropower projects face evolving challenges, Nepal has a strong foundation to ensure the sector continues to thrive. The expansion of the national grid, climate-related disruptions and changing energy demand patterns require new approaches, but they also present opportunities for innovation and adaptation. Research at Kathmandu University and the University of Bristol (IRENA, 2023b) has explored the potential of turbines that could enhance Nepal's ability to harness hydropower in high-silt river environments. Meanwhile, efforts to integrate micro-hydro systems with productive uses of electricity, such as supporting agriculture and small businesses, are helping boost economic sustainability and increase energy demand. Additionally, community-driven landscape management strategies are being explored to mitigate the risks of flooding, landslides and changing precipitation patterns. With its strong technical expertise, a well-established workforce and a proven community-based model, Nepal remains a global leader in micro-hydropower, demonstrating how decentralised renewable energy can power rural development and inspire similar initiatives worldwide.

3.1.4. Biomass

Technology definition and description

Biomass can be defined as a variety of organic materials that can be used to produce electricity, generate fuels for transportation or be used in other domains such as cooking or industrial processes. This guidebook will focus on the use of bioenergy to generate electricity.

The materials that can be considered are wood and wood processing waste, such as pellets, firewood or other derivatives, agricultural residues from various types of cultivation, municipal waste from organic materials such as paper, wool products or food, human and animal manure, or algae (US Energy Information Administration, 2025).

To produce electricity, the materials listed above can be burned (direct combustion) to heat a boiler, using the resulting steam to rotate a turbine. Before burning, biomass sources usually undergo various processes that make them more energy efficient. Wood residues can be dried, ground into dust and compressed into pellets. Alternatively, biomass can be heated at around 200–320°C to dry it out. This process usually allows the final material to retain 90% of its original energy.

Alternative methods consist of storing and heating solid biomass materials into a pressurised chamber to alter their state through decomposition. This is referred to as thermochemical conversion and results in the production of biogases that can then be burned to produce electricity.

Biogases contain a varying composition of methane, carbon dioxide and other gases, with methane typically ranging between 45 and 75% of the biogas volume depending on the type of material that is being decomposed. These biogases can be upgraded to produce biomethane, which is a purer form of renewable gas containing almost exclusively methane. Biomethane can also be obtained through the process of pyrolysis, which heats woody residues in a compressed, oxygen-free chamber at temperatures between 400 and 500°C. This process transforms around 30% of the original wood mass into charcoal, and 70% into biomethane. Biogases can be burned in a thermal power plant to, once again, heat a boiler and spin a turbine through the resulting steam, generating electricity.

Bioenergy is classified as a renewable source because it releases into the atmosphere CO2 that was stored in plants during their life cycle through the process of photosynthesis. This absorption happens with greater intensity during the growth stage. Younger, growing forests are therefore able to store much more CO2 than mature forests, which are instead closer to a net zero carbon state, releasing as much carbon through matter decomposition as they are able to absorb through photosynthesis.

Advantages and disadvantages

Bioenergy will play an important role in the energy transition. In its pathway to net zero by 2050, the IEA projects the use of modern bioenergy sources to more than double by 2050, while traditional use of biomass is phased out (IEA, 2023c).

In its current state, solid biomass or biogases can be used in a co-firing mechanism to produce electricity alongside standard fossil-fuel sources. This can be seen as a valuable option when viewing global warming through a transition perspective. Coal and natural gas power plants can last for several decades before being decommissioned, and adding a renewable source of fuel can help abate emissions as we strive to achieve net zero. This can be done through directly milling biomass residues together with coal, indirectly converting solid biomass into biogas or biomethane and then burning these gases together with coal, or with standard natural gas, or finally through the process of parallel co-firing, which means burning bioenergy in a separate boiler and adding the resulting steam into the steam originating from fossil fuels.

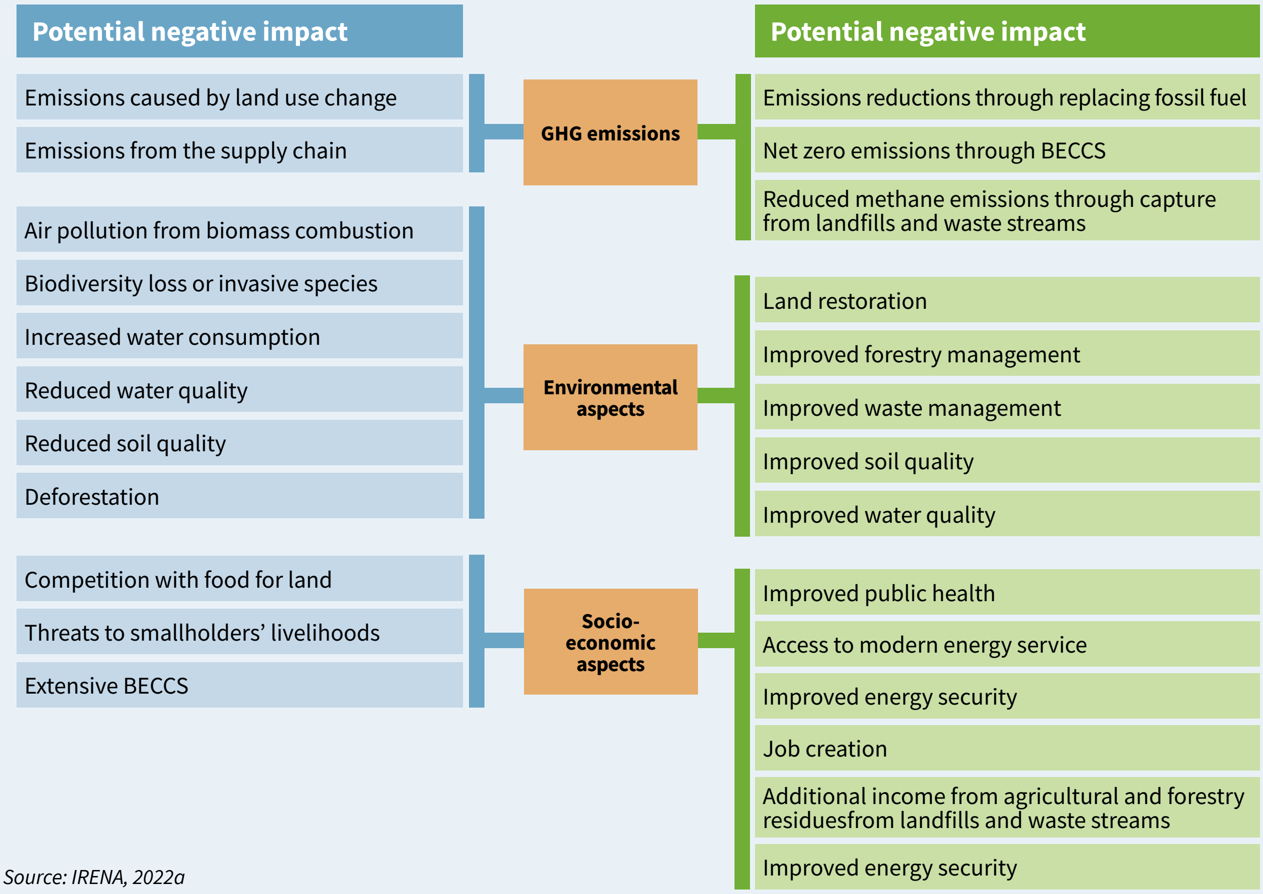
Biomass can also be used as the sole source of fuel for electricity generation, fully phasing out fossil fuels altogether. In this case, bioenergy would serve a similar purpose as fossil fuels, which is to provide baseload and a rapid source of flexibility to the grid when supply from variable electricity sources such as solar PV or wind is not available. Because of the thermal nature of the process needed to transform biomass into electricity (combustion and steam turbine), existing coal or natural gas plants can therefore be converted into bioenergy plants, decarbonising important segments of the electricity system while preserving the advantages that are provided by fossil fuels, such as baseload and flexibility of operation.

If not managed well, bioenergy supply chains and use could, however, lead to with negative environmental, social or economic impacts, including beyond the energy sector related to transport, land-use, rural development and waste management (IRENA, 2022a). Such impacts are highly context-, location- and scale-dependent (IRENA, 2022a). Figure 3.3 includes some of the potential benefits and negative impacts related to bioenergy sustainability.

As mentioned above, bioenergy is theoretically carbon-neutral because the CO_2 released into the atmosphere through its burning was stored in a plant during its life cycle. Technically speaking, this process is considered neutral against the geological timing of Earth. The urgency of achieving net zero GHG emissions by 2050, however, means that burning bioenergy might imply anticipating the release of a quantity of CO_2 into the atmosphere that might have otherwise been released decades, if not centuries, into the future, complicating even further our path to carbon neutrality. Moreover, bioenergy has a higher likelihood of retaining its strict carbon-neutral quality if sourced locally, to reduce emissions from transport. Currently, large quantities of bioenergy sources are traded internationally, which adds carbon emissions to their life cycle and creates emissions accounting issues. Countries burning such resources for electricity can declare zero emissions from the process, and source countries cutting down the resource must add CO_2 to their emissions accounting for land use change.

To shorten the carbon debt time for bioenergy and to increase the likelihood not only of achieving emissions neutrality, but of reaching negative emissions, bioenergy can be coupled with bioenergy with carbon capture and storage (BECCS) technology to store emissions in the ground instead of releasing them back into the atmosphere. BECCS is essential to deliver the negative emissions needed to reach the 1.5°C threshold by 2050, if the use of bioenergy is preferred. Retrofitting plants with these technologies could, however, incur significant cost and take a long time.

Figure 3.3: Potential aspects related to bioenergy sustainability



Source: IRENA, 2022a

Economic assessment and affordability

Unlike solar PV, wind and hydro, in bioenergy the feedstock component of LCOE costs is an important share of total costs, usually between 20 and 50% (IRENA, 2024g). Because of the high variability of feedstock that can be used in a bioenergy electrical plant, costs can vary substantially and are very site-specific. Some plants in the developing world have demonstrated that they can reach very low LCOE costs, with plants near industrial processing sites using residues from those activities displaying costs that are close to zero. On the other hand, LCOE costs in more advanced economies are usually higher due to the tendency of using more wood-derived materials. On the low-cost end of the spectrum are residues from sugar cane, rice and paper processing (IRENA, 2024g). A proportion of the feedstock cost is connected to transporting it to the power plant – minimising the distance between the feedstock source and the plant will thus reduce these costs. As climate change progresses, the availability of some types of feedstock will be called into question, or their seasonality will be disrupted. This will, of course, vary from stock to stock and will have to be studied more accurately in the future.

Total installed costs for bioenergy depend largely on the region of the world. In general, however, bioenergy plants tend to be smaller in size because of the relatively low energy content of bio feedstock. Enlarging the size of the plant to accommodate for larger numbers of feedstock would disproportionally augment costs per kW.

LCOE and installed costs in 2023 situate bioenergy in the middle-higher range of the spectrum when compared with other renewable energy sources (Figure 3.2).

Mitigation and net zero potential

As mentioned above, bioenergy is theoretically a net zero carbon energy source, since the release of CO_2

that results from burning organic material was previously stored inside the material during its life cycle. This can play an important role in transitioning energy systems away from fossil fuels.

This is only true, however, for material that is sourced locally and that does not require an excessive number of processing steps. As organic feedstocks are traded at greater distances, or even internationally, and as processing intensifies and grows in complexity, so may the GHG (GHG) emissions from the feedstock life cycle increase. The UNFCCC estimates that an average power plant dedicated exclusively to the burning of bioenergy will release approximately 230 gCO_2eq/kWh during its lifetime (Figure 2.1), the vast majority of which is connected to infrastructure and supply chain emissions. Electrifying, or increasing the use of renewables in transport and treatment processes, would be an important first step to diminish these emissions. Alternatively, sourcing feedstocks locally would greatly contribute to tackling this issue.

A crucial concern with bioenergy involves the displacement of natural, mature forests. 'Good' bioenergy projects, in fact, use waste from industrial processes to produce electricity that would have otherwise resulted in the release of CO_2. Trading and selling such waste products, however, may potentially create harmful incentives for the displacement of forested areas to increase volumes in the industry generating such waste. A classic example is the use of discarded kernels from palm oil plantations – these products can legitimately be classified as organic waste but selling them internationally can inventivise the expansion of the industry and the deforestation of areas in Southeast Asia to replace them with palm oil plantations. Moreover, it is important to note that while afforestation efforts will, of course, balance out the CO_2 released into the atmosphere through the burning of bioenergy, this will incur a 'carbon debt'– that is, the temporal gap that exists between burning CO_2 all at once, and the time it takes for a new tree to grow and remove that same amount of CO_2 from the atmosphere. Estimates indicate that converting tropical rainforests to palm plantations, for example, would take 86 years for that carbon debt to be paid back (IRENA, 2022a).

Expanding purpose crops for bioenergy could, however, be undertaken in lands that are considered as degraded, and that are not currently being used for food crop cultivation, or are not occupied by forests. This would avoid carbon stock loss, in addition to preserving ecosystems.

The adoption of BECCS would be another way to mitigate indirect emissions from bioenergy. These are a set of processes to remove CO_2 emitted into the atmosphere and store it in the ground. The most natural 'BECCS process' is afforestation, or tree planting. Young, growing forests are incredibly efficient at storing carbon and provide a host of other benefits to the environment and the ecosystem. This process must however be complemented by human-made processes. These can be deployed at various stages of the conversion from feedstock to energy. Post-combustion, these practices usually involve separating CO_2 from the released gases using a liquid solvent. This is a technique that can also be applied in biodigesters producing biogas, and that can be retrofitted onto existing plants. Another means is biochar (Energy Futures Initiative, 2022). Through the process of pyrolysis described previously, biomass feedstock is heated at temperatures between 400 and 500°C inside a compressed chamber to produce biogases (70%) and charcoal (30%). While both biogas and charcoal can be used to produce energy, the latter also functions as a perfect storage of CO_2 and can be placed underground with the added benefit of improving soil fertility.

BECCS processes are a crucial component of the wider set of carbon capture and storage technologies, which are in turn crucial for the attainment of net zero by 2050. Their use is, however, still limited and can be traced to only a handful of successful examples. The IEA indicates that despite encouraging developments, we are currently not on track to develop BECCS to their necessary capacity to keep our climate from warming more than 1.5°C (IEA, 2025). Currently, around 2 million tonnes of biogenic CO2 (CO2 from biomass) are captured each year – projects currently under development would bring this total to 60 million tonnes. While this is a respectable increase, the IEA indicates this would need to increase to 185 million tonnes by 2030 (IEA, 2023c). At the moment, BECCS processes and technologies face high costs that range from USD 88 to USD 288 per tonne of biogenic CO2 (IRENA, 2022a).

In short, bioenergy can be considered as holding a high potential to be carbon-neutral if it is sourced, and transformed, locally, and if it uses biomaterial from already existing industrial or agricultural processes, or sources its biomass from purpose crops grown on marginal lands, without impacting forested areas. In this case, bioenergy is an excellent source of electricity that can provide the same flexibility and manoeuvrability advantages provided by fossil fuels, acting as potential baseload and ramp up when supply from solar PV and wind fails.

Just Transition aspects

Bioenergy requires vast amounts of land, which is inherently limited. Bioresources destined for energy production may compete with nature preservation efforts and the agricultural resources needed for a growing population. Biomass should not go against the efforts of the energy transition by leading to deforestation and undermining food security. Bioenergy projects should reduce these potential negative impacts by adopting measures like sustainable regenerating biomass stocks and assessing the current and future land needs of the local community. Improving soil quality may also lead to higher efficiency and biomass yields (IRENA, 2022a). Another effective approach is to focus on waste feedstocks, such as agricultural residues and organic municipal waste. This strategy not only reduces pressure on land but may also offer extra revenue opportunities for local farming and waste collectors. In fact, other organisations argue that nearly all future bioenergy needs could be met through the use of waste, meaning there would be no need to expand the land already used for biofuel production (Energy Transitions Commission, 2023).

The use of bioenergy should ensure that benefits reach the local communities where the bio feedstock is sourced and energy production is located, creating employment and income opportunities. Another measure to promote a just energy transition is offering vocational trainings to up- and reskill workers in the agriculture and industrial settings, with due consideration being paid to women and future generations.

Despite these potential advantages to the local economy, the combustion process in bioenergy produces air pollution that can seriously harm respiratory and cardiovascular health. This issue is especially severe when biomass is used for indoor cooking with little or no ventilation. It is vital to focus on clean cooking solutions and to carry out biomass energy production under controlled conditions, and to build biomass energy production facilities at a sufficient distance from residential areas, ensuring that harmful emissions do not affect nearby communities. Lastly, another risk factor that should be considered and mitigated is the use of pesticides and fertilizers for growing bioresources can negatively impact land and water resources.

Enhancing climate resilience of energy technologies

Climate change can shift the areas where suitable crops can grow. It can also impact bioenergy crop cultivations through more intense droughts, longer periods of aridity and extreme heat.

- Governments can increase wildfire resilience by adopting a holistic approach to fire management while considering bioenergy projects. These strategies should ideally be harmonised with forest product manufacturing and community protection (IEA Bioenergy, 2024).
- Fire-resistant species can provide greater resilience by crop cultivations, as well as identifying candidate genes that enhance crop resistance to drought and higher temperatures.
- Crop management techniques can be modified through crop rotation patterns to decrease drought stress on crops, or increase crop diversification to positively impact the physical properties and water storage in the soil. Selecting the best types of species combinations in areas affected by drought will be crucial (Benitez-Alfonso et al., 2023).

Barriers to dissemination / development

The technologies required to produce electricity from biomass are widely available and have reached full maturity. However, several barriers to their application have been identified (EUBIA, 2025):

- Operational barriers resulting from the potential unavailability of feedstock, as well as changing seasonal patterns that can increase uncertainties, difficulties in managing a plethora of small landowners generating such feedstock, and the challenges resulting from installing proper treatment processes and techniques so as to not degrade feedstock energy content.

- Costs related to transportation from different locations, retrofitting of existing plants with processing technologies and BECCS, as well as co-firing biomass with coal, need to be considered. Currently, biomass costs are still not overall competitive with fossil fuels and other renewables. However, this depends on the location, and on feedstock supply and treatment costs. Co-firing of biomass and coal at 25% has shown that operational costs per kWh could increase up to 20% (IRENA, 2022a), although studies on a specific project in China have shown that biomass co-firing of up to 20% at biomass prices between USD 50 and 100/Mt is an economically viable alternative (Wang W., 2023). This poses financing challenges due to concerns arising from the long-term viability of feedstock supplies, and the complex contracting nature with a number of smaller suppliers.
- Adapting plants with BECCS technologies can also pose a challenge of an economic, as well as a technical, nature. Appropriate incentive measures should be applied in this case, because BECCS could counterbalance some of the issues related to local sourcing – storing biogenic emissions from biomass combustion can make up for more stretched supply chains, which could decrease contracting complexity.

Potential measures to offset these complexities vary from subsidies and grants, to renewables obligations providing extra income to producers through trading certificates, the use of auctions and long-term power purchase agreements, and blending mandates for biofuels.

Solutions in the real world

In Punjab, India, a 12 MW paddy straw power plant has demonstrated a sustainable and community-driven model for utilising agricultural residues for energy (IRENA, 2019c). One of the key challenges in biomass energy is the efficient collection, separation and processing of crop residues. To address this, a biomass supply chain was established, enabling farmers to sell their paddy straw instead of burning it, thereby reducing air pollution and improving soil health. The supply chain operates through a village level entrepreneur model, where local entrepreneurs are trained and equipped with necessary tools to collect, process and transport biomass to the power plant. This system not only creates rural jobs and boosts local incomes, but also reduces GHG emissions by preventing open-field burning. The model aligns with India's Clean Energy and Climate Change initiatives, while also improving energy security by reducing dependence on fossil fuels.

The success of this biomass supply chain has led to its expansion into multiple sectors, including biofuels, biogas and hybrid renewable energy projects. Companies involved in the initiative have worked with government agencies, multinational corporations and policy think tanks to refine biomass logistics and develop scalable business models. The system has empowered over 500 entrepreneurs, created thousands of rural jobs and provided a new revenue stream for farmers, increasing their income by USD 1,000 to USD 2,500 annually. Additionally, the initiative has supplied clean energy to industries such as pharmaceuticals and food processing, reducing reliance on conventional energy sources. While challenges remain, including financial support for infrastructure, policy alignment and overcoming traditional farming habits, the growing awareness of biomass as a valuable resource suggests a promising future for sustainable rural energy in India.

3.1.5. Geothermal

Technology definition and description

Geothermal energy means harnessing the heat from beneath the Earth's crust to provide direct heating, or to power a turbine and generate electricity.

At its core, our planet is composed of molten metals, primarily iron and nickel, compressed into a solid state and reaching temperatures above 5,000°C, or hotter than the surface of the sun. As we move away from the core and towards the crust, we approach the mantle, which is a 2,800 km-thick layer of rock with varying temperatures between 3,700°C, closer to the Earth's core, and 1,000°C closer to the crust.

Traditionally, geothermal technology combines permeable rock formations underground and heat located close to the surface and created by volcanic activity. Pressure from underground forces water, or steam, upwards through the porous rock. At temperatures between 90 to 150°C underground, the water is vaporised and the high-pressured steam that rushes upwards through the hole can rotate a turbine and a generator to produce electricity. For commercial-scale electricity production, temperatures between 150 and 180°C are recommended. The hotter the underground temperature is, the higher the pressure at which the water steam is pumped upwards and the larger the turbine will be.

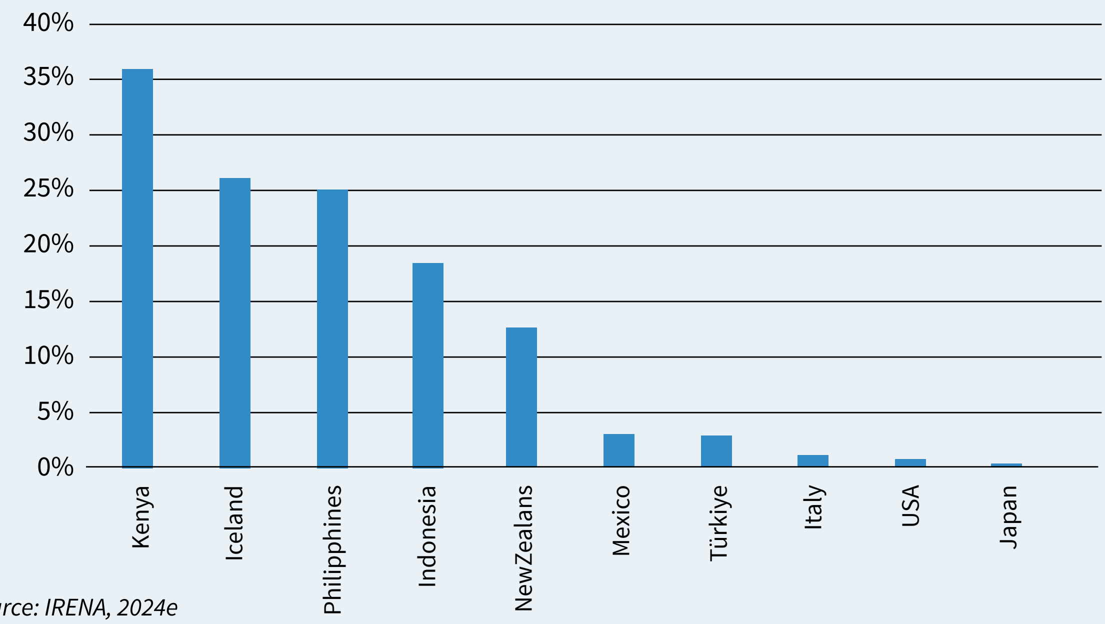
The vapour can be condensed and pumped back into the hole, where the whole process can begin anew, consuming only the electricity required to run the water pump itself.

While this process can seem quite straightforward, the deployment of geothermal technologies has so far been limited. Globally, this energy resource has grown only 32% in terms of installed capacity between 2014 and 2023 (IRENA, 2024e). In comparison, overall renewable capacity has grown by 129% in the same period, and some resources in particular have experienced a stellar rise – solar capacity has grown by 689%, wind by 191%.

Geothermal capacity has so far been installed in meaningful quantities in locations sitting atop significant volcanic activity, usually straddling or close to tectonic plates, where the higher temperatures required to rotate a turbine are located closer to the surface and are thus more accessible and economical to reach. In some of these countries, such as Iceland, the Philippines, Kenya or Indonesia, installed geothermal amounts to close to, or more, than 20% of total installed renewable energy capacity (Figure 3.4).

Geothermal plants in such locations can tap into aquifers at comparatively lower depths, or can drill to lower depths than normally required to find the temperatures suitable to generate steam at such a level of pressure to generate electricity.

Figure 3.4: Top geothermal energy utilizers by share over total installed renewable energy capacity



Source: IRENA, 2024e

Not all countries are, however, able to harness high-temperature water steam from ground depths as shallow as in countries with abundant volcanic and geothermal activity. In all other locations around the world, wells must be dug deeper to access the necessary temperatures to achieve electricity generation, which means higher costs. A binary steam plant can help in this case – hot water below 100°C is carried from the extraction well into a heat exchanger containing a secondary working fluid at lower boiling temperatures. The hot water heats up this secondary liquid, which in turn generates the steam to spin the turbine and generator and produce electricity. Such advances have allowed generating electricity at temperatures as low as 70–80°C, although at limited scale only.

Other technological applications can allow for a more widespread adoption of geothermal energy. Enhanced, or engineered, geothermal systems (EGSs) adopt techniques already developed by the oil and gas industry, such as horizontal drilling and fracking, to improve the permeability of rock layers beneath the surface by creating fractures within it and injecting high-pressured water, and then extracting its steam through the extraction well. The application of these technologies essentially allows a geothermal project to create the necessary conditions for success (permeable rock, a water basin and high temperatures at accessible depths) everywhere on Earth's crust, and could allow for an expansion of this energy source. Furthermore, the technology presents cost-reduction potential as it receives more attention. The US National Renewable Energy Laboratory has published a pathway in which it charts a 90% reduction in the cost of this technology through reduced drilling costs and increased well productivity (NREL, 2023).

IRENA estimates that the worldwide potential of geothermal energy is 5,000 GW, enormously larger than the capacity that is currently installed (15 GW), and far more geographically widespread than economics and technology have allowed for until recently (IRENA, 2023a).

Advantages and disadvantages

Geothermal is not as cost competitive as the two cheapest renewable resources, solar PV and onshore wind (Figure 3.2), but it has some advantages:

- It provides a continuous, reliable production of electricity, which can serve as a source of baseload in complementarity with intermittent sources such as wind and solar energy (IRENA, 2023a). This makes geothermal particularly suitable to the power and mining industry.
- It can work in complementarity with minerals extraction (IRENA, 2023a). Lithium, a critical material used in the manufacturing of chemistries in ion-lithium batteries, will become ever more important as the electrification of the transport system and the adoption of utility-scale batteries gathers pace. Current lithium extraction methods are energy-intensive (spodumene mining) or cause substantial stress on existing water resources (salt brine method). Extracting lithium from geothermal water reservoirs can provide an extra source of income and accelerate the energy transition while producing electricity (US Department of Energy, 2025).
- Geothermal can provide both water heating and electricity. Flash steam geothermal plants are a technology that separates vapour from water particles to provide both services simultaneously and that can be used in urban or peri-urban settings (IRENA, 2023a).
- The stable, reliable nature of geothermal electricity generation is also suitable for the production of green hydrogen.
- Finally, geothermal sites can function as suitable storage space for carbon capture and storage technology, in complementarity (IRENA, 2023a).

Geothermal's drawbacks can be summarised in terms of development and operational costs, as well as its limited (for now) geographical scope. To develop the resource, three conditions must be met simultaneously – the presence of water underground, the permeability of the rock layer and the correct temperature to generate enough steam pressure to power a generator. Until now, these three conditions have coexisted in a state that is economically feasible to exploit only in a handful of realities located atop areas of significant tectonic activity, where heated aquifers could be accessed at shallow depths or where permeable rock formations at high temperatures could be found not far from the surface. This has limited the exploration of this resource as costs for solar PV panels and wind turbines have plummeted.

The adoption of fracking and horizontal drilling technologies from the oil and gas industry promises to expand the geographical scope of geothermal energy, but may be accompanied by the controversies that have accompanied these technologies until now. The potential to generate earthquakes cannot be underestimated. Although a rare phenomenon, soil subsidence due to hydraulic fracturing for geothermal plants has already occurred in both Germany (Sass et al., 2010) and New Zealand (Bromley et al., 2015).

Finally, what can be considered as an asset (reliability and continuous electricity production) can also be considered as liability in a grid system characterised by ever more variable renewable energy. Traditional geothermal is not a flexible resource as the upwards flow of water, or steam, from underground cannot be controlled or modulated. This does not allow geothermal to rapidly ramp up, or down, electricity production to compensate for solar PV or wind's variable output. Closed loop systems can present a potential solution to this problem – boring equipment drills a U-shaped hole into the ground, using it as a conduit to pump water downwards, run it through the horizontal section of the hole to allow it to heat up, and push it back up from the other side. With water flowing through a sealed tube and with its flow regulated more accurately, this technology can function as a form of storage. However, it requires more underground infrastructure and therefore higher costs.

Economic assessment and affordability

Current geothermal capacity is as competitive as offshore wind and bioenergy in terms of LCOE (USD 0.071/kWh) (IRENA, 2024g), even though the weighted average is determined by a comparatively small number of projects due to its low deployment.

It is comparatively difficult when developing a geothermal project to determine its future costs. Assessments of underground temperatures, of rock permeability, or of the existence of underground water reservoirs are expensive to conduct and can lead to negative results. Globally, the accuracy and performance of prospective wells can be assisted with better geological mapping, but success in one project does not automatically convert into success in another development. Despite this, following globally accepted standards and procedures remains to date the best way to guarantee the development of a successful geothermal project (IRENA, 2024g). Operational complexities also distinguish geothermal from other renewable energy sources. The constant transfer of a liquid from an underground reservoir through a system of wells creates a dynamic situation that requires constant attention and a potential shift in operations. Lastly, the exhaustion of existing wells can cause additional operational costs as new wells need to be developed.

Nevertheless, the future cost profile of geothermal systems is currently in flux as new technologies such as enhanced geothermal systems, large-scale closed-loop or sedimentary geothermal are on the brink of being deployed at larger scale. In Indonesia, in particular, advanced modelling techniques and new practices in the management of geothermal reservoirs are already being deployed in fruitful ways.

Mitigation and net zero emissions potential

According to the IPCC, geothermal energy produces 38 gCO2eq/kWh during its life cycle (see Figure 2.1). This puts geothermal in the top section of GHG emitters among renewable energy technologies, behind bioenergy and solar PV, but above hydro, CSP and wind energy. It is worth noting that these emissions are only a tiny fraction of what is released by fossil fuel plants.

Most of these emissions are released through the manufacturing and installation of the components and equipment needed for a geothermal plant. Moreover, geothermal power plants are currently located in areas of intense volcanic activity, where CO_2 is naturally present and released into the atmosphere. Any extraction of fluids from underground can cause an increase in emissions release and therefore result in a carbon footprint from the plant's operation.

That being said, geothermal can be considered as a clean source of energy and presents few downsides from a mitigation perspective, even compared to other renewable sources.

Just Transition aspects

The potential environmental and socioeconomic impacts from geothermal energy projects should be addressed from the start of the project. While geothermal energy emits minimal amounts of GHGs compared to fossil fuel power plants, they do release gases like hydrogen sulphide, carbon dioxide and methane. These gases can result in severe health impacts if the power plant exceeds the permissible threshold. Geothermal energy plants can also lead to unintended biodiversity loss, and groundwater and surface water pollution. For example, if a geothermal power plant discharges geothermal fluid near a water body, these discharges from the power plant can lead to changes in the chemical composition and temperature of the water body, potentially affecting aquatic life in it and the life and livelihoods of communities that depend on these ecosystems (Rotich, 2024). To minimise these impacts, modern geothermal power plants can be equipped with, for example, carbon capture for gases and closed-loop systems, in which the fluid is reinjected underground rather than it being discharged to the environment. To ensure the well-being of local communities, surveys of health effects should not only focus on short-term effects. Instead, they should also consider the long-term consequences of exposure to gases, heavy metals and other pollutants.

Local populations should be compensated fairly for their land when ceded to a power plant and its related infrastructure. Water consumption is also high in geothermal facilities, especially during drilling in the exploration process. This may have implications for water access to local communities, especially in areas where water is an already scarce resource. The drilling and exploration of geothermal energy can also lead to increased seismic activity, increasing the potential of a landslide. It is important to conduct studies for this risk, implement actions to minimise any potential impacts, and keep local communities informed about these possible hazards. The project developers, government officials and other parties involved should ensure transparent communication with local communities. The stakeholders should consult community interests from the beginning of the project, incorporate rigorous environmental impact assessments, restore damaged habitats and continue monitoring to ensure compliance with environmental standards.

Barriers to dissemination / deployment

The production of electricity through geothermal is faced with a series of challenges:

- Technological: improvements in geological mapping are necessary to enhance resource estimation and reduce exploration costs. Additionally, costs for drilling equipment, which has to withstand incredibly high temperatures when digging deep, will have to come down further to facilitate the expansion of this technology.
- Financing: because of remaining uncertainties related to resource exploration and estimation before the technology can come to economic fruition, financing is still relatively hard to come by. Moreover, many projects still require an overhaul of the policy framework to become competitive, as well as encountering regulatory hindrances in the form of complex permitting and licensing procedures.

Solutions in the real world

Comoros is advancing its geothermal energy sector as part of a broader effort to reduce reliance on imported fossil fuels and enhance its energy security. Currently, the country's electricity generation is dominated by thermal power (93%) (IRENA, 2020b), making it vulnerable to global fuel price fluctuations and supply disruptions (African Development Bank, 2024). To address this, the country has prioritised the Karthala Geothermal Exploration Project, which focuses on harnessing the geothermal potential of the Karthala volcano on the island of Grand Comore. Studies conducted since 2015 indicate a high-temperature geothermal system capable of producing over 40 MW, with plans to install an initial 10 MW capacity through the drilling of three exploration wells. This initiative serves to align the country with its 2030 development agenda, the African Union's Agenda 2063 and Comoros' global climate commitments, particularly in reducing GHG emissions and diversifying the country's energy mix.

Beyond energy security, this project plays a crucial role in sustainable economic development and community resilience. High electricity costs have historically limited economic opportunities and increased social vulnerabilities, particularly for rural populations and women-led households, where energy access is crucial for livelihood activities. The project aims to boost local employment, with approximately 150 jobs created during the exploration phase, including a dedicated quota for women to address gender disparities in the energy sector. Additionally, the infrastructure development – such as access roads and water supply systems – will provide lasting benefits to local communities, improving agricultural productivity, market access and tourism around the Karthala volcano. However, challenges remain, including technical expertise gaps, high upfront investment costs and governance issues in the power sector.

To ensure long-term success, the project includes capacity-building programmes, international cooperation with Kenya's Geothermal Development Company and institutional reforms to attract private-sector investment. If successfully implemented, the geothermal initiative could become a cornerstone of Comoros' just energy transition, promoting resilient infrastructure, economic diversification and sustainable development.

3.1.6. Marine energy

Technology definition and description

Harnessing the energy released by water movements in our oceans is the latest frontier in renewable energy. Today, installed marine energy capacity worldwide is almost negligible, at a mere 527 MW, or 0.01% of the total global installed renewable energy capacity (IRENA, 2024e). Moreover, little progress has been made in recent years – in the last 10 years, only 13 extra MW of capacity were added.

Marine can be subdivided into a few main types:

- Tidal energy: these technologies harness the natural rise and fall in water levels brought about by gravitational forces between the Earth and the Moon. The potential of this type of resource is limited by geographical constraints and is thus the smallest of any other type of marine energy technology (1,200 TWh per year) (IRENA, 2020e). Currently the most mature way to harness the flow of water between high and low tides is through a dam and turbine reminiscent of basin hydroelectric projects (tidal barrage), a method that has already been in limited use since the 1960s. Other practices that are approaching commercial use are underwater turbines, while other innovations are still in the research and prototype stage such as oscillating hydrofoil or tidal kites.
- Wave energy: this type of technology harnesses the kinetic energy transmitted by the wind onto the ocean surface, which manifests as waves. Because it is not geographically constrained like tidal energy, wave has a vastly superior potential, about 29,500 TWh worldwide (IRENA, 2020e). This type of technology, however, is currently characterised by a plethora of prototypes that have not yet coalesced into one single technological best practice and are still not available at commercial scale, with a 30-year delay behind other energy sources like solar or wind. However, research efforts are intensifying and may yield promising results in the coming years.

These two technologies present different levels of maturity, with tidal energy displaying a much more advanced stage of large-scale commercialisation. Much of the wave-energy projects being tested and deployed are on the other hand still on a much smaller scale (IRENA, 2020e). Alternative ways to harvest the energy of the ocean exist and are currently being researched, but are still at the testing level (IRENA, 2020e). These will be analysed in a later section of this guidebook (New technological advances).

Advantages and disadvantages

Ocean energy is a clean energy source that does not emit any carbon emissions into the atmosphere through its operation. Moreover, its LCOE might be lower than previously anticipated – despite the difficulty to predict future trends and despite the lack of data and the dearth of available projects to study, research on active projects has suggested some cautious optimism in this regard.

Tidal energy is highly predictable and is very well suited to complement variable renewable energy sources like solar PV and wind. Wave energy, on the other hand, is less predictable but can be well suited to be paired up with offshore wind. Co-locating offshore wind farms and wave energy sites can make economic sense from a transport cost perspective, since the same ships will be used to carry wind turbine components on site and will transport maintenance crews whose costs can be distributed among the two different resources. It also makes sense from an energy complementarity perspective – researchers have analysed wind patterns off the coast of California and determined that combined systems could decrease variability and unpredictability when operating together, due to offshore wind speeds peaking in the summer, and waves reaching their maximum size in the winter. The decreased co-variability cannot yet be considered as a universal feature of combined wave and offshore wind farms, but it presents a promising complementarity to explore further (Gideon et al., 2021).

A special use for a predictable energy source such as marine energy is for desalination projects. Water scarcity will likely increase in the future due to climate change, and desalination will increasingly become an indispensable process to ensure continued irrigation and the general sustenance of life in the most water-deprived areas. Desalination is, however, energy-expensive, and can be supplied by energy sources closer to the coast, especially in areas where there is no connection to the grid. Marine, in complementarity with offshore wind, can provide a feasible solution.

SIDS could provide an ideal market to deploy these technologies – in combination with other renewables, they could provide the bulk of electricity production in island settings alleviating state budget funds dedicated to the import of diesel. In addition, electricity in island states is often carbon intensive and comparatively costly, and marine energy would provide a comparatively cheap alternative.

Finally, investments in ocean energy infrastructure can be coupled with necessary investments in coastal defence infrastructure – as sea levels rise, new barriers, bridges and other protective infrastructure will need to be set up. Merging this expense with electricity generation could bring down costs for this technology.

Marine energy can, however, be difficult and expensive to maintain. It faces engineering challenges by design, in the form of a constant attrition by the forces of the sea, by particularly strong storms, by the corrosive action of salty water, or by invasive marine species such as barnacles or algae (biofouling) (Yang et al., 2017). This translates into a need to design equipment and structures able to withstand the constant subjection to these forces, and a need for frequent maintenance, which is by definition costlier the further offshore.

The effects of marine energy on the environment must still be studied with accuracy. Given the plethora of designs being tested, their effects can be varied. Marine life can be disturbed by underwater cables (Pirttimaa L & Cruz, 2020). Turbines in more tested tidal barrage systems have been observed disturbing, and even killing, fish species. Turbines placed underwater in a stream tidal system can also cause harm to marine life.

Economic assessment and affordability

LCOEs for marine energy are difficult to assess and their trajectory is hard to predict. Relatively few assessments have been conducted, among which a Strategic Energy Technology (SET) Plan by the European Commission. This study reported costs from 18 projects worldwide and assessed them against the cost reduction targets set by the SET Plan Declaration of Intent on Ocean Energy (EUR 0.15/kWh for tidal and EUR 0.20/kWh for wave energy). The study reveals that in 2019 tidal energy showed a reduction of more than 40% in their reported LCOE ranges (EUR 0.34–0.38/kWh) compared to three years before. Wave energy projects, on the other hand, still did not present enough evidence to prepare an assessment (Magagna, & Sales Agut, 2019).

The expectation is that additional deployment and research will reduce these costs further, according to IRENA, which cites similarly dramatic costs in LCOE learning curves after the infancy stage of now mature technologies such as wind and solar. In its study, IRENA assesses the current LCOE for tidal energy at USD 0.20–0.45/kWh, and USD 0.30–0.55/kWh for wave energy (IRENA, 2020e).

Mitigation and net zero potential

Ocean energy has by definition an enormous mitigating potential – the electricity generated by the movement of water is carbon-free. As other renewable energy resources, however, they may generate indirect life cycle emissions tied to the construction of components and infrastructure. Because of their limited application, additional research on this topic must still be conducted. Existing studies point to emissions being released at the manufacturing stage, through the construction of turbines, buoys and turbine propellers, as well as for mooring equipment. The materials used for these technologies, moreover, is still very energy-intensive (steel, tin, concrete, cast iron) (Paredes et al., 2019). Regarding emissions potentially produced during operation, additional studies should probably be conducted.

Ocean energy is regarded as a potentially breakthrough technology to achieve net zero emissions by 2050. The IEA, in conjunction with Ocean Energy Systems (OES), has provided a roadmap in late 2023 detailing the requirements to ensure that an extra 300 GW of ocean energy capacity is added by 2050, emphasising the high importance of this technology for mitigation efforts in the next decades (IEA Ocean Energy Systems, 2023).

Just Transition aspects

Marine energy is still a relatively nascent technology, and its potential socioeconomic and environmental impacts have not been as widely studied as those of other conventional renewable energy technologies. This applies particularly to its life cycle and biodiversity impacts. Marine energy projects should continuously assess and monitor impacts on marine animals, which in turn could affect the lives and livelihoods of communities that rely on marine ecosystems.

Marine energy technologies present opportunities and benefits for the local economy, particularly around employment and energy resilience. It is estimated that wave energy converters (WECs) have the potential to create more than 10 jobs per megawatt (Chrisdameria et al., 2024), with jobs created through the development and maintenance of installations. As marine energy deployments expand, it is essential to carefully retrain workers from other sectors. This is especially relevant in SIDS, where even minor changes in the energy system can lead to significant impacts. Prioritising local hiring over international workers can ensure more benefits are directed to local communities. To achieve this, educational and research programmes, in partnership with the marine energy project developers, can help prepare the skilled workforce needed for this growing sector. Looking further, studies have shown that manufacturing components in nearby ports reduces capital costs and creates local jobs, allowing the local or regional economy to capture more of the value-added benefits of this technology and improving the economic feasibility of the project. Lastly, the development of marine energy technology projects can increase resilience of local economies by improving energy access and reliability.

Barriers to dissemination / deployment

The challenges to the dissemination of existing marine technologies are of a technological, financial and supply chain nature.

- Technological: as mentioned above, marine energy technologies have to operate in harsh environments and must be designed to withstand the constant application of natural forces in the form of currents, water corrosion, salt particles and infestation by marine life. In the past, such issues have caused bankruptcies (Garanovic, 2023), even hampering operations for successive projects needing to remove stranded equipment left on the seabed (Gorman, 2023). Installing the necessary infrastructure is also a relatively complicated process, requiring extensive technical expertise and incurring high capital costs.
- Financial: LCOEs for marine energy are still significantly higher than other renewables and are thus still not competitive in a normal scenario where other options are available. The lack of tested prototypes, especially in wave energy, also tends to increase costs related to research and development. This is an issue that can be solved with additional research, advocacy and education, which will in turn contribute to diminishing the risk perception of these technologies.
- Supply chain: because of the hitherto limited extent of these solutions, few standardised production processes exist and developers must often come up with ad hoc solutions. Supply chains have also not developed to such an extent as to notice the degree of specialisation that can be observed for other renewable technologies, with developers often doubling as component manufacturers due to the lack of supply.

New technological advances

Tidal energy is the most mature branch of this energy technology, having existed in operation in limited form since the 1960s. Wave energy is one step behind – various commercial entities are now experimenting and testing their prototypes – in a technological evolutionary race that sets them more or less in the same place that solar PV or wind occupied 30 years ago (IRENA, 2020e). Other ways to harness the energy of the ocean are one step behind further and are being tested in research labs and universities. It is worth providing a brief explanation of these technologies as we could hear more about them in coming years:

- Ocean Thermal Energy Conversion (OTEC): As the sun heats up the surface of the ocean, substantial temperature differences can exist between the uppermost layer of the ocean and the ones beneath it. In tropical areas between latitudes of 30 degrees north and 30 degrees south, this temperature difference can be quite substantial, above 20°C. Thermal conversion processes can harness these temperature differences to generate electricity – these processes flash evaporate the warm water on the surface to generate steam and rotate a turbine, using cold water to condense the vapour. Another process uses warm water to heat up another working fluid at a lower boiling temperature. Given that these two are both processes being used in geothermal applications, a spill-over effect is thus possible. A 2022 pre-feasibility study by the UN Climate Technology Centre and Network (CTCN) for a project in Nauru, in the meantime, observed very little impact of this technology in terms of space occupied by infrastructure, as well as a considerable reduction in diesel fuel imports as a consequence of its deployment, signalling potential advantages from this technology (CTCN, 2022). Japan has made significant strides in developing and implementing this technology. In Kumejima, a small island located in Okinawa

Prefecture in the southern part of Japan, OTEC and DSW plants have been operating for approximately 10 years, demonstrating not only the soundness of technology but also positive impacts on climate change mitigation and adaptation, as well as sustainability benefits to local community, which is the so-called 'Kumejima Model'. In 2024, a feasibility study was conducted by Ministry of Economy, Trade and Industry of Japan and partners to examine the technical and economic aspects of installing a deep-sea water intake facility for OTEC in Mauritius including identifying a candidate site based on scientific data, developing a schematic design, conducting financial assessment and business modelling with electricity, water, and cooling supply and demand, as well as showing finance options.

- Salinity Gradient Energy (SGE): This type of technology harnesses the differences in pressure between water with a high salt content and fresh water. As river estuaries flow into the sea, fresh water encounters salt water. If fresh water and salt water are separated by a membrane, molecules from the former will tend to migrate to the latter, applying pressure on the membrane that can be used to spin a turbine. This process was discovered in the 1950s, and is currently being tested in research facilities.

Solutions in the real world

The Wave Energy Project in Ada Foah, Ghana, is moving towards revival after years of delays (Renewable Energy World, 2019). The project, led locally by a Ghanaian renewable energy company, aims to establish Africa's first large-scale wave energy park. Originally initiated in 2015, the project saw successful pilot tests, where power was successfully integrated into Ghana's national grid. However, after the initial deployment phase, progress stalled, leaving the project in limbo. Now, under a new agreement with external actors, the next phase will begin at 5 MW, with a planned expansion to 100 MW within 24 months and an eventual goal of reaching 1,000 MW under a power purchase agreement with the Electricity Company of Ghana.

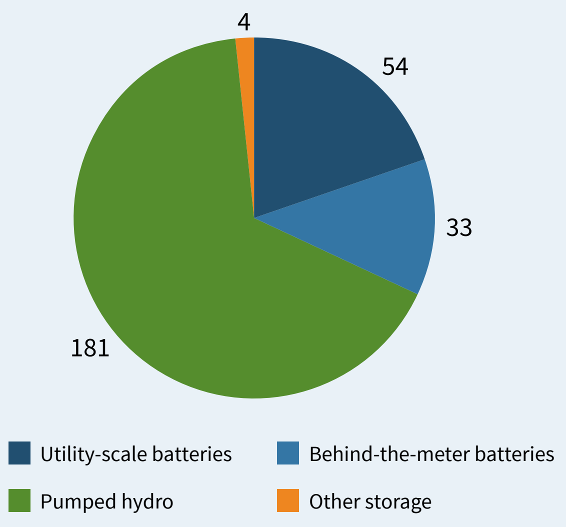
Beyond its potential as a landmark renewable energy project, the wave energy park is expected to deliver significant social, economic and environmental benefits for Ghana, if successfully operated. The cost of electricity from the project is estimated to range between 3–4 cents per kWh, making it cheaper than existing hydro and thermal power and reducing dependence on fossil fuel imports. Additionally, the project has the potential to create jobs across multiple sectors, including manufacturing, operations and maintenance, with opportunities for local assembly of non-core technology as the project scales. Challenges remain however, illustrating the obstacles that this technology may still encounter. These challenges include the successful execution of financing agreements, maintaining investor confidence and ensuring steady progress beyond the initial phases. Local leaders, such as Naana Dagojo Domaley I, the Paramount Queen mother of Ada, have urged developers to fulfil their promises (Modern Ghana, 2024), and emphasised the importance of the project for community development and industrial growth.

3.2. Energy storage technologies

Storage will be a key resource to counter the negative impacts of variable electricity generation, introducing much-needed flexibility to the grid.

Today, the most utilised form of storage is pumped hydro, followed by batteries (mostly lithium-ion), and all other forms of storage occupying a distant third place, as shown in Figure 3.5.

Figure 3.5: Types of storage capacity in 2023 (GW)



Source: IEA, 2024b

3.2.1. Pumped hydro

Technology definition and description

As explained in the hydropower section of this guidebook, pumped hydro connects two basins of water at different levels of altitude. In times of peak electricity demand, water is released from the top basin through a conduit and into the basin below, spinning a turbine to generate electricity. When electricity supply is at its peak, it is used to power a pump to push the water uphill and back into the upper-level basin, where it will be stored until the next time. This form of storage can be accessed rapidly and is by far the cheapest system at utility scale.

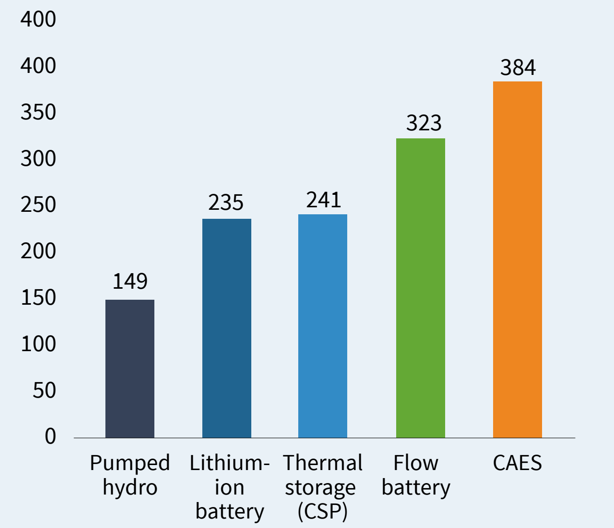
Advantages and disadvantages

Pumped hydro can be coupled or integrated with variable renewable energy. One way to do this is to combine a pumped storage system with floating solar PV, which would at the same time reduce water evaporation by exposing less water surface to the sun and utilise the water in the basin to cool and clean the solar panels as part of their regular maintenance. Such a system would also solve the issue of solar PV farms occupying too much space. Just like standard hydropower dams, moreover, pumped hydro can perform ancillary services, such as providing water for agriculture.

Pumped hydro is already a flexible and nimble storage system. The rapidity with which it can meet demand can be increased even further by technological advances, such as variable speed turbines that allow these facilities to reach full output in less than 30 seconds (IRENA, 2020g). As explained above, this key feature will enable pumped hydro to become a crucial feature in tomorrow's electricity system, providing much needed ramping capacity without subjecting system infrastructure to wear and tear.

On the other hand, pumped hydro is subjected to some of the same limitations that affect other hydroelectric systems – geological and terrain specificities restrict its deployment especially when compared with other storage systems. Moreover, rising temperatures brought by climate change may increase water evaporation and decrease its effectiveness during droughts.

Figure 3.6: Cost of different storage technologies (2023 USD/kWh)



CAES = compressed air energy storage
Source: IRENA, 2024g

Economic assessment and affordability

Pumped hydro is currently the least expensive of all available storage technologies (Figure 3.6), and offers relatively low storage costs compared to other technologies. In 2023, the cost of water storage in pumped hydro plants averaged at USD 148 per kWh.

Cost reductions in pumped hydro storage (PHS) have been driven by innovations in digitalisation, remote monitoring and predictive maintenance, which help lower both capital and operational expenditures and increased the attractiveness of investments in these technologies. Moreover, integrating pumped hydro with variable renewable energy sources such as wind and solar can optimise energy use by reducing curtailment and increasing system efficiency, further enhancing its cost-effectiveness. While battery storage solutions are increasingly used for short-term energy needs, pumped hydro remains therefore the dominant large-scale storage technology (IRENA, 2024e; IRENA, 2024g) due to its affordability, long-duration storage capabilities and co-benefits, such as freshwater storage.

Mitigation and net zero potential

Pumped hydro plays a crucial role in mitigating the unpredictability of variable renewable energy such as wind and solar, making it an essential technology for achieving net zero emissions. Moreover, unlike battery storage, which primarily addresses short-term intermittency pumped hydro provides seasonal storage capacity, making it a valuable tool for smoothing out fluctuations in renewable generation over extended periods.

The integration of pumped hydro with floating PV systems in reservoirs further enhances the efficiency of renewable energy utilisation by reducing evaporation losses, improving solar panel efficiency through water cooling and leveraging existing transmission infrastructure to supply dispatchable, flexible power.

Additionally, pumped hydro can help mitigate curtailment of renewable energy, ensuring that surplus generation is stored and later dispatched when demand is high, such as Kyushu in Japan or the El Hierro wind-pumped, hydro hybrid plant in Spain (IRENA, 2020g). By reducing reliance on fossil fuel-based backup generation, pumped hydro supports the phasing out of thermal power plants, thereby lowering carbon emissions and aiding in the transition towards a net zero energy system. With global hydropower capacity expected to increase by two-thirds by 2050, doubling pumped hydro capacity to 325 GW will be essential in meeting the world's long-term renewable energy storage needs while advancing climate mitigation goals.

Just Transition aspects

Pumped hydro installations are often in remote locations, where the project can provide a considerable stimulus to the local economy. While more jobs are generated in the construction phase than in the operational phase, construction can last more than five years, requiring civil engineers, among other skilled workers across the supply chain (Turner et al., 2020). With conventional hydropower projects, land is submerged to build an upper and lower water reservoir. Nearby residents who would be affected by the development of a pumped hydro facility, must be consulted from the start of the project. Transparent communication must be ensured, and no activity should take place without consent and fair compensation for the affected population. Historically, most of the burden has typically been implicated on rural, indigenous and the most economically disadvantaged groups. Allowing these groups to express their views and concerns and have active involvement during the entirety of the project must be ensured. Impacts to fishing communities as well as access to drinking and irrigation water should be evaluated. In many cases, the obstruction of the waterway has impacts on migratory fish and the availability of sufficient water downstream. Economic benefits and energy services must reach local communities. This includes investing tax revenues from the pumped hydro installation into priority areas such as schools, public infrastructure and energy access.

Enhancing climate resilience of energy technologies

As climate change increases the frequency and severity of droughts, storms and extreme weather events, pumped hydro technologies are adopting measures to maintain their reliability. As stated previously, one approach is integrating floating PV systems on water reservoirs, which thereby reduces evaporation losses and conserves water resources in regions affected by droughts. Additionally, given the closed-loop nature of pumped hydro, risks associated with changing river flows and water scarcity can be mitigated.

Digitalisation and remote monitoring can further protect pumped hydro technologies against extreme climate events by enabling operators to carry out predictive maintenance, which helps detect potential system failures before extreme weather events occur, reducing downtime and costly repairs. The fast-ramping capabilities of pumped hydro allow these plants to quickly adapt to grid instability caused by sudden climate-induced demand shifts or renewable energy supply drops.

Barriers to dissemination / deployment

Despite its advantages, pumped hydro faces several barriers to widespread dissemination and deployment.

A major barrier is high capital costs, as pumped hydro projects require significant investments in infrastructure, including dams, tunnels, turbines, generators, excavation and land acquisition, leading to costs of 370 to 600 USD per kilowatt (kW) of installed capacity.

Additionally, long project lead times associated with site selection, environmental assessments and permitting processes can delay project development, making it less attractive compared to faster-to-deploy battery storage solutions.

Another challenge is the geographical limitations: pumped hydro requires specific topographical, geological and hydrological conditions to be viable, which restricts deployment to suitable locations. Closed-loop systems can counter some of these limitations by being independent of naturally flowing water sources, but they still require significant land and infrastructure investments.

Regulatory and market barriers finally also play a role, as traditional electricity markets may not properly value the long-term storage and flexibility benefits of pumped hydro systems, making it harder for projects to secure financing and investment incentives. While a key insight for Technology Action Plans (as is true for most storage technology) is that the remuneration of services provided within energy markets should consider generation, capacity and complementary services provided, it is in fact not clear what would be the exact element that needs to be considered in terms of the valuation of long-term storage. Additionally, while digitalisation and predictive maintenance have helped reduce operational costs, the technological complexity and need for skilled workforce in maintaining and optimising pumped hydro facilities may present additional hurdles in certain regions.

Finally, competition from alternative storage technologies, such as hydrogen and battery storage, which are receiving increasing investment and innovation, could slow the expansion of pumped hydro.

Solutions in the real world

The Frades II pumped-storage hydropower plant in Portugal serves as an important flexibility mechanism for managing variable wind and solar generation (IRENA, 2020g). The facility features two variable-speed reversible units with an output of 390 MW each, making it the largest variable-speed, pumped-storage plant in Europe. The plant plays a key role in stabilising the Portuguese grid, and allows excess electricity from renewables to be stored by pumping water to an upstream reservoir and then generating power when needed. The project was developed as part of a broader hydropower expansion strategy that leverages existing dam infrastructure.

Beyond its technical achievements, Frades II has had a positive socioeconomic and environmental impact. During construction, the project directly benefited the local economy, with 40% of the workforce sourced from the region and 20% of subcontracted companies based locally. The developer also launched entrepreneurship and energy efficiency programmes in partnership with regional business schools, helping foster sustainable economic development.

3.2.2. Battery storage

Technology definition and description

Utility batteries are rapidly rising to become the preferred system of choice to store electricity. Today, they range from a few MWh to hundreds of MWh (IRENA, 2019e) and have represented over 65% of new battery capacity for power generation in the last 10 years (IEA, 2024a). The technology that has outgrown all others in these past 10 years is by far lithium-ion devices, which has surpassed all other battery chemistries in the late 2010s due to rapidly falling prices.[5]

Advantages and disadvantages

Batteries are increasingly becoming the preferred storage choice due to their split-second responsiveness, which allows for rapid frequency regulation as well as an extremely flexible ramping of electricity production when needed, which enables utility operators to flatten the 'duck curve' (see section 3.3). Moreover, utility-scale batteries can be co-located with power plants to provide a restart of production in case of system failure (black start).

Finally, just like pumped hydro, batteries can store non-dispatchable excess electricity generated by variable renewables, avoiding curtailment and optimising these resources. Differently from pumped hydro, however, batteries are not geographically constrained, nor is their performance jeopardised by climate change affecting raining patterns. These features allow batteries to be deployed not only at different scales, but also as a backup system for distributed renewable energy such as

5 This guidebook will concern itself only with batteries connected to transmission and distribution systems. Behind-the-meter batteries will not be considered within the scope of this study and may be covered in future publications focusing on demand-side technologies.

mini-grids, which will be essential to achieve the universal energy access objectives laid out by the SDGs.

Some large-scale batteries are now being adapted to multi-hour energy storage, compensating for prolonged periods of lower generation (IEA, 2024a). These are redox flow or iron air types of batteries, which are better suited for these purposes. The use of utility-scale battery storage in the future will, however, likely focus on energy shifting, i.e. functioning as capacity reserve during peak hours, thereby replacing other power generation technologies and deferring investments in these power plants. In a future world, more and more utility-scale batteries could replace, together with pumped hydro, the role currently being played by hydroelectric power plants.

Battery manufacturing and availability may be limited by supply-chain restrictions for some of the essential minerals that compose their chemistries, which may in turn manifest in price volatility (IEA, 2024a). Alternative chemistries using different minerals are however beginning to emerge and to challenge the current dominance of lithium-ion, offering a potential diversification of battery supply. Lithium iron phosphate (LFP) is characterised by lower costs, higher cycle life and better safety standards (IEA, 2024a), while sodium-ion batteries need fewer critical minerals to produce and may thus be less susceptible to these supply chain constraints, although their benefits should be weighed against the price of lithium as well as a potentially shorter life span (IEA, 2024a).

Economic assessment and affordability

The costs of both utility-scale and small-scale battery storage options have declined significantly over the past decade, driven by technological advances, economies of scale and increased global manufacturing capacity. Between 2010 and 2023, the cost of fully installed and commissioned battery storage projects dropped by 89%, from USD 2,511/kWh to USD 273/kWh, with further declines expected as installed capacity for utility-scale batteries expands from 54 GW in 2023 to 585 GW in 2030 (IRENA, 2024b).

Lithium iron phosphate batteries have emerged as the dominant chemistry for stationary storage, accounting for 84% of new additions in 2023 due to their lower costs, higher cycle life and improved safety compared to nickel-based, lithium-ion batteries. They have also been associated with the largest drops in prices – with recent auctions in China recording record-low prices ranging from USD 60.5 to 82.kWh (Parkinson & Hill, 2024).

Despite short-term fluctuations due to raw material price volatility, the long-term trend indicates continued cost reductions, making both utility-scale and small-scale battery storage increasingly economically viable.

Mitigation and net zero potential

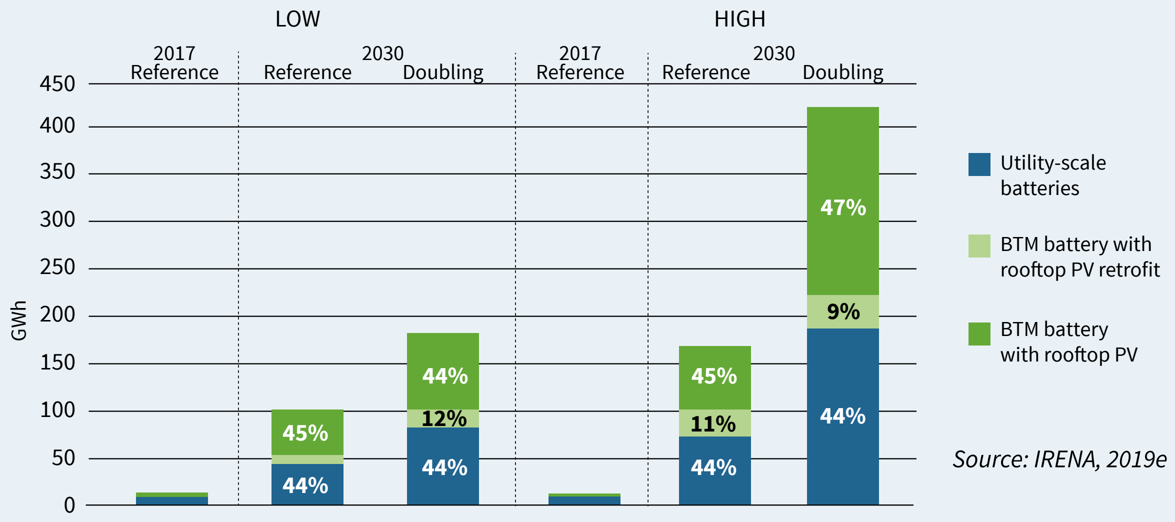
Battery energy storage systems play a crucial role in mitigating climate change and advancing the net zero transition. Utility-scale battery storage enhances grid flexibility by storing excess renewable electricity generated during periods of high supply and injecting it back into the grid when demand rises, thereby reducing curtailment of clean energy and displacing fossil fuel-based peaking plants.

Large-scale batteries also help balance supply and demand, provide frequency regulation, flexible ramping, and black start services, and enable the decarbonisation of isolated and off-grid communities that would otherwise rely on expensive, high-emission diesel generation.

The decreasing costs of lithium-ion batteries, particularly LFP technology, have accelerated both grid-scale and household battery adoption, making these storage systems a more affordable and scalable solution for reducing emissions in the power sector.

In remote regions and islands, where energy generation is historically dependent on fossil fuels, battery systems paired with renewables have allowed for a near-complete shift away from diesel. Moreover, as their capacity increases (Figure 3.7), both large-scale and small-scale battery storage systems will remain key enablers of a net zero energy future, ensuring clean, dispatchable and reliable electricity, while minimising carbon emissions across power grids and distributed energy networks.

Figure 3.7: Stationary battery storage's energy capacity growth (2017–2030 GWh)



Source: IRENA, 2019e

Just Transition aspects

Battery energy storage systems can offer multiple benefits to local communities. In many rural areas across the world, decentralised mini-grids have become a viable solution to ensure electricity access. Most of these mini-grids are based on solar energy, therefore relying on solar irradiation during the day, leaving communities without electricity access during the night when it is needed in households for activities, such as studying and cooking, and preventing businesses from continuing to operate. Battery storage systems can extend energy access into the night by collecting surplus solar energy during the day and dispatching it when needed during nighttime. In this way, battery storage systems can play an important role in empowering marginalised communities, by improving the economic feasibility of mini-grid projects, and reducing reliance on diesel generators and cooking with biomass. With large-scale battery storage facilities, habitat destruction may occur during the construction of the system and its related infrastructure. To reduce such impacts, opportunities to repurpose existing infrastructure, such as decommissioned coal power plants, as battery systems should be explored. In this way, roads, electricity grid infrastructure and the site itself can be used for a new battery storage facility. Examples of this already exist in the United Kingdom and others are being scoped in the United States (Marshall, 2024; Ciampoli, 2024). Another benefit that battery storage systems deliver to the community is the improvement of local electricity infrastructure and reliability.

Although this section has focused on the Just Transition aspects relating to the deployment of battery storage systems, special consideration should also be given to the resources needed to build them. This includes the materials required in the cathode, anode and electrolyser of the batteries – namely lithium, copper, nickel, manganese, cobalt and phosphorous. Sourcing these materials should be carried out responsibly, following the principles of a just and fair energy transition. This means addressing environmental impacts to water pollution, GHG emissions, biodiversity loss and chemical waste, as well as engaging with local communities and improving the livelihoods of local communities through guaranteeing fair labour conditions, fair wages and safety regulations on mining sites. Lastly, for local communities to benefit from local battery storage system installations, local hiring should be involved in the construction, operation, maintenance and dismantling of the project, and locally manufactured components should be promoted. Partnerships with local businesses and educational institutions can lead to a well-prepared workforce that can support the project and create additional local employment opportunities.

Enhancing climate resilience of energy technologies

As extreme weather events become more frequent due to climate change, enhancing battery energy storage resilience will become ever more critical. Unlike pumped hydro storage, which is vulnerable to droughts and changing hydrological patterns, batteries offer geographical flexibility and can be deployed in locations less susceptible to climate-related risks.

Rising temperatures, however, can affect battery performance. Advances in battery chemistry, however, can enhance battery thermal stability and cycle life, making these technologies more resilient to high temperatures and degradation over time (IRENA, 2019e). As the frequency and intensity of climate-related disruptions increase, both large-scale and small-scale battery storage solutions will be essential for bolstering energy resilience, ensuring power continuity, and supporting climate adaptation strategies worldwide.

Barriers to dissemination / deployment

Despite its growing importance in grid flexibility and renewable energy integration, the widespread deployment and dissemination of utility-scale battery storage face several key barriers.

- High upfront costs: these remain prohibitive in many settings despite significant cost reductions in recent years, with project developers often finding projects financially unfeasible.
- Regulatory and policy constraints: these limit the expansion of large-scale battery storage, as many existing electricity market frameworks were designed without considering the dual role of batteries as both energy consumers and energy suppliers. To overcome these barriers, pilot projects are essential for demonstrating technical feasibility, financial viability and business models for battery deployment.

Addressing these barriers through policy reforms, financial incentives and knowledge dissemination will be crucial for unlocking the full potential of utility-scale battery storage in supporting the clean energy transition.

Solutions in the real world

The Victorian Big Battery (VBB) is a 300 MW / 450 MWh lithium-ion energy storage facility located near Geelong. Developed by Neoen in collaboration with Tesla and AusNet Services, the battery stablises the Australian grid particularly during periods of peak demand and high renewable energy penetration. By discharging stored energy when needed, this system manages to mitigate fluctuations in electricity supply, as well as reducing the risk of load shedding and enhancing overall grid reliability. Beyond providing frequency control and emergency reserves, the VBB also serves as a buffer for integrating increasing shares of wind and solar power, addressing intermittency challenges associated with renewable energy sources.

From an economic and environmental perspective, this system offers cost savings and efficiency improvements. Analyses suggests that for every dollar invested, the battery is expected to deliver over $2 in benefits to households located in the areas, as well as businesses, via lower wholesale electricity prices and enhanced energy security (Victoria State Government, 2023). This facility's ability to store excess renewable energy and to discharge it when required reduces the State's reliance on thermal fossil fuel plants, and manages thereby to decrease emissions and to support Victoria's target of 50% renewable energy by 2030. Additionally, given its fast response time, the battery system enhances the overall stability of the power system, reducing the likelihood of blackouts and allowing more efficient utilisation of the existing transmission infrastructure.

3.2.3. Thermal, geothermal storage

Technology definition and description

Other types of storage have already been referred to in this guidebook and compose the majority of the remaining capacity of 4 GW.

Thermal storage refers mainly to CSP, which uses a system of mirrors to concentrate solar light onto a central tower containing a molten salt solution. This solution is released in times of peak electricity demand to heat water and rotate a turbine through the resulting steam. While originally a competitor to solar PV, CSP lost out during the early-to-mid 2010s due to higher costs and more difficult manoeuvrability. It has, however, emerged as a potential thermal storage solution, especially in countries with desert-like environments, high solar irradiance and plenty of space.

Enhanced geothermal systems have also been touted as a potential new form of energy storage. Drilling deep underground and creating artificial heated water and steam reservoirs, these power plants can double as storage facilities through their ability to hold energy-generating fluids for days at a time, unlike lithium-ion batteries, in addition to displaying flexibility for ramping up electricity production in times of need (World Economic Forum, 2022b).

Other types of solid-state storage solutions are being developed, such as solid-state concrete storage serving as a cheaper alternative to CSP, or in the form of rocks. The latter method can be used to store renewable electricity.

Advantages and disadvantages

Thermal storage can be used to regulate the outputs of variable sources of renewable electricity. These technologies have longer lifespans than batteries and are submitted to lower amounts of degradation, requiring fewer maintenance and replacement interventions.

These storage technologies may also be adapted to sector integration, linking power generation to demands in other sectors. Conversion of excess power to heat, for example, may be of use for housing heating purposes, making these storage options adapted for end-use consumption. This function can also help reduce stress on the system as electrification gathers pace, potentially decoupling heat demand from the grid.

Finally, thermal storage is well suited for seasonal storage, especially in areas experiencing a substantial change in thermal load between seasons. In this case, surplus heat produced through solar PV in the summer, for example, can be released in winter when production is lower (IRENA, 2020f).

Despite all this, some barriers still remain to the systematic deployment of thermal storage options. The relative immaturity of technologies or systems keeps cost higher than competing storage options, while some reliability issues have been noted, related to the corrosive nature of molten salts in CSP plants. Similarly, issues may arise from the recurring need of a certain amount of backup energy to minimise the risk of salt freezing (IRENA, 2020f).

Just Transition aspects

Thermal energy storage can play a role in enabling Just Transition policies: converting decommissioned coal power plants into thermal storage units preserves jobs while using existing infrastructure to supply zero-carbon energy to industries and data centres (Ding et al., 2024). Thermal storage also allows communities to manage their own energy supply while reducing dependence on fossil fuels (Elliot et al., 2025).

Economic assessment and affordability

CSP, the most available form of thermal storage system, has experienced some cost reduction, albeit not as sharply as the cost reductions in solar PV or in wind turbines. Between 2010 and 2023, LCOE costs have fallen by 70%, from USD 0.393/kWh to USD 0.117/kWh. These costs might, however, not be too representative especially in later years, as very few new plants have been commissioned in this period of time.

Installed costs, at the same time, declined by 37% in the same period, while average global capacity factors increased from 30% in 2010 to 55% in 2023, a sharp increase that brightens prospects for this type of technology (IRENA, 2024g).

Barriers to dissemination / deployment

The deployment of these thermal energy storage technologies faces several barriers that hinder their dissemination across sectors and regions.

- Lack of knowledge and awareness: with heat and cold often taking a back seat in climate change mitigation efforts, most attention is focused on decarbonising electricity and transport. This limited focus results in insufficient investment in thermal storage research, development and demonstration projects.
- Technology immaturity: many of the existing projects are still not commercially viable, with many new systems still in the early stages of technology readiness.
- Uncertainty on energy system developments: the type of thermal storage option required will vary with the type of technology chosen to generate electricity, with storage options depending on potential paths to determine their requirements in terms of storage needs, timescales, locations and temperature ranges. This uncertainty makes it challenging to establish clear, long-term policies and investments for these technologies.
- Limited recognition of thermal storage in policy and regulatory frameworks.
- Competition from other energy storage technologies, such as batteries and green hydrogen. This

introduces a complex landscape where TES must demonstrate its unique advantages and fit within local energy systems to gain traction.

Solutions in the real world

Morocco is highly suited to generating power from solar PV and 60% of its territory has a potential of generating from 18 to 19 MWh at peak performance in a year (IRENA, 2019a). In comparison, less than 20% of the world's land area on average can yield this type of energy output. As discussed above, however, the high intermittency of solar PV technologies necessitates a flexible grid and, equally importantly, a sophisticated storage system to provide electricity also when there is no sunlight. The Ouarzazate Noor Concentrating Solar Power (CSP) station is the world's largest form of thermal energy storage facility.

CSP operates like a system of mirrors to concentrate sunlight into a central tower, usually containing a conductive liquid such as molten salt. The liquid heats up and is pumped down to a water-containing generator at night, generating steam and in turn powering a turbine to generate electricity.

Projects such as these necessitate an abundant quantity of direct sunlight and are particularly suitable in desert environments. Growing optimism towards CSP's potential as the main solar generating technology peaked in the early 2010s, but solar photovoltaics' dramatic cost decline made the latter technology more competitive. Moreover, operational complexities for CSP, such as the necessity to maintain the temperature of the molten liquid inside the central tower at a stable level, have also contributed to tilting the choice in favour of photovoltaics since the 2010s.

The capacity of CSP to generate electricity at night, however, makes it a perfect complementary substitute to PV when the latter cannot generate any electricity. Moreover, at the moment CSP is still cheaper than other alternative storage technologies (such as large-scale, lithium-ion battery systems), especially when acting as a backup generator for longer times, such as a whole night, discussed further in the 'thermal, geothermal storage' section.

3.2.4. Green hydrogen

Technology definition and description

Hydrogen can be used as an energy carrier and industrial feedstock. When burned, it produces water vapour. In order to produce pure hydrogen, water or other molecules that contain it must be split using abundant quantities of energy. There are various processes that can be used to generate hydrogen in its pure form – the process that involves exclusively renewable energy yields "green hydrogen", and will be the focus in this guidebook.

Green hydrogen is produced through the process of electrolysis, which utilises electricity to split water into hydrogen and oxygen atoms. If the electricity used in this process is derived entirely from renewable sources, then the process can be considered 100% carbon-free except for the life cycle emissions responsible in the manufacturing of the electrolysing equipment and the transport of the hydrogen gas for trading purposes. Regardless, molecular hydrogen leaking into the atmosphere during conversion has an indirect radiative forcing effect due to interaction with atmospheric methane that is assessed as being around 5.8 times stronger than the same amount of CO_2 (Forster et al., 2007). Green hydrogen can be used in fuel cells to produce electricity, making this, so far, the only dispatchable energy source that can store electricity for days, weeks, even months.

Electrolysers are an essential step to obtain this form of hydrogen atoms. They are devices that generate hydrogen molecules by splitting water using electrical current. If one were to zoom in on an electrolyser, progressively peering into its structure, one would notice:

1) The electrolyser system, which includes its main electrolysing component (the stack containing the electrolysing cells) as well as essential corollary equipment for cooling, converting the electricity input, processing the generated hydrogen;
2) Zooming in, the stack, which contains a series of cells that carry out the electrolysing process. The stack contains other components such as spacers, seals and frames;
3) Zooming in even further, the cells are composed of two electrodes immersed or adjacent to a medium transporting the generated chemical charges. The type of medium can change depending on the type of electrolyte technology.

There are four main types of electrolyte cell technologies (IRENA, 2021a), with potential advantages and disadvantages to be considered (see Table 2).

Table 2: Types of electrolyte cell technologies

Technology Type	Advantages	Disadvantages
Alkaline: Uses a liquid alkaline solution (KOH) as an electrolyte with porous diaphragms to separate gases A well-established technology with a relatively simple design and long operational lifetime	• Simple and robust design • Well-established and mature technology • Relatively easy to manufacture • Long lifetimes (above 30 years) • Lower capital costs compared to PEM • Can operate at high pressures (up to 200 bar) • Proven track record of stable operation • Does not require expensive noble metal catalysts • Can achieve efficiencies comparable to PEM with modern designs • Electrodes can be protected using small idle currents to enhance durability	• Uses high-concentration potassium hydroxide, requiring careful handling • Gas intermixing risk, limiting operational flexibility • Thick diaphragms increase resistance, reducing efficiency • Lower current density compared to PEM • high ohmic resistance with spacers • More challenging to operate at differential pressures • Gas permeation can cause diaphragm degradation over time • Sensitivity to water impurities such as iron, chromium and copper • Electrodes can suffer from gradual deactivation without protection measures
Proton Exchange Membrane (PEM): Uses a solid polymer membrane (PFSA) as the electrolyte, offering high efficiency and compact design Operates well under high pressures and has a fast response time, but relies on expensive materials	• Higher efficiencies due to lower resistance • Compact and simple system design • Operates at high pressure differentials (up to 70 bar) • Robust PFSA membrane enables stability • Rapid response to load changes • Can operate at higher current densities than alkaline electrolysers • Expected future lifetime of more than 100,000 hours with continued R&D • Higher operational flexibility, making it well suited for integration with renewables • Electrochemical system design supports modular scalability	• Expensive due to need for noble metal catalysts and titanium components • Sensitive to water impurities (iron, copper, chromium, sodium) • Limited validated lifetime for large-scale MW units • Thicker membranes required for differential pressure, reducing efficiency • Additional catalyst needed to re-convert permeated hydrogen • Higher operating pressures can cause stress on membranes, reducing durability • Susceptible to voltage fluctuations when integrated with variable renewable energy
Anion Exchange Membrane (AEM): A newer technology combining elements of alkaline and PEM electrolysers Uses anion exchange membranes to conduct OH-ions, allowing for non-noble catalysts and simplified system design Still in early development with stability and conductivity challenges	• Potential combination of benefits from Alkaline and PEM • Does not require noble metal catalysts or titanium components • can operate under differential pressure • Simpler system design (similar to PEM) • Lower cost potential than PEM due to fewer expensive materials • Offers potential improvements in efficiency through new membrane designs	• Low maturity level; limited commercial deployment • Stability issues with AEM membranes • Poor electrode architectures and slow catalyst kinetics • Lower conductivity of OH-ions compared to PEM • Requires either thinner membranes or higher charge density, impacting durability • Membrane collapse and catalyst dissolution occur rapidly without improvements

Solid Oxide: Operates at high temperatures (700–850°C) using a ceramic electrolyte Can integrate waste heat for increased efficiency and co-electrolyse CO_2 and H_2O to produce syngas Still largely in experimental and demonstration stages due to material degradation issues	• High-temperature operation improves reaction kinetics • Uses cheaper nickel electrodes • Can achieve apparent efficiencies above 100% (due to heat integration) • Potential for reversible operation (electrolysis & fuel cell mode) • Can co-electrolyse CO2 and H2O to produce syngas • Less reliance on precious metal catalysts compared to PEM • Can be coupled with waste heat sources to improve efficiency	• High operating temperatures lead to faster degradation • Limited commercial deployment (mainly at kW-scale, some 1 MW projects) • Sealing challenges at high differential pressures • Stack degradation due to contaminants (e.g., silica, interconnect materials) • Difficulties in handling thermal cycling and ramping • Shorter lifetime (around 20,000 hours) compared to other technologies • Requires careful operational strategies to avoid frequent cooling cycles

Electrolyser current costs need to come down drastically to escalate their production and allow green hydrogen to become more widely used. The European Union (EU) has set targets for electrolyser capacity to 80 GW by 2030 – this target is likely to be missed: current electrolyser capacity has increased substantially in the EU in the last years, but green hydrogen production was still negligible in 2023, 0.2% of total hydrogen production (Dolci et al., 2022). According to IRENA, government loans, capital grants and other forms of financial assistance can kickstart this industry in a meaningful way. Other measures include an improved tax scheme, paying a premium through feed-in tariffs and increasing support for research (IRENA, 2020d).

White hydrogen, that is naturally occurring hydrogen generated by geochemical reactions in hard rock, can also be used for energy purposes. Because it is naturally occurring, it presents no production costs, compared to green hydrogen. Although still not a viable alternative to green hydrogen and still not usable at scale, interest in this resource is growing.

Advantages and disadvantages

The main advantage of green hydrogen comes from its capacity to store energy for very long periods of time. According to IRENA, hydrogen storage might occupy the same role as storage of natural gas. The difference being that natural gas storage is used to meet short-term and highly seasonal demand requirements, whereas demand from hydrogen is likely to be more constant (IRENA, 2025b).

Like other forms of storage, hydrogen can be produced in the summer months, when electricity is cheaper, and used in winter months to compensate for electricity supply downturns from variable renewable sources. In this sense, the use of hydrogen as a storage source should not be viewed as in competition with other shorter-term forms of storage, such as batteries, but rather as a complementary tool. Short-term storage systems provide immediate flexibility, whereas green hydrogen enables more long-term energy management (IRENA, 2025b).

However, long-term hydrogen storage presents specific challenges that must be addressed. Depending on how hydrogen is stored, whether as a compressed gas or in cryogenic liquid form, there are energy losses associated with compression and liquefaction. Cryogenic storage, in particular, requires continuous energy input to maintain extremely low temperatures, leading to boil-off losses over time. Additionally, leakage risks must be considered, as hydrogen molecules are small and can permeate materials more easily than other gases, potentially leading to storage inefficiencies and safety concerns (IRENA, 2020c).

To fully leverage hydrogen's role in long-term energy storage, strategies to minimise energy losses, improve storage infrastructure and enhance system efficiency will be essential.

Economic assessment and affordability

Green hydrogen costs depend largely on the type of electrolyser technology being deployed.

PEM and alkaline electrolysers, despite their market maturity and availability, remain highly expensive compared to fossil fuel-based hydrogen production. PEM electrolysers, in particular, are 50–60% more expensive than alkaline systems, posing a significant barrier to widespread adoption. While both technologies have potential for cost reduction through economies of scale, automation and increased component availability, challenges persist, especially for AEM and solid oxide electrolysers, which remain in early commercial stages. These emerging technologies face higher costs due to limited manufacturing capabilities and smaller system sizes (only up to a few kW), making their cost structures more difficult to evaluate compared to their more established counterparts. However, AEM electrolysers hold an advantage over PEM in cost-reduction potential since they can avoid expensive materials like titanium, which contributes significantly to PEM stack costs.

A challenge in estimating electrolyser costs lies in data availability and inconsistent cost boundaries across studies. Costs can be analysed at three levels:

1) the cell unit, where the core electrochemical process takes place;
2) the stack, which includes bipolar plates and other small components;
3) the full system, which encompasses the balance of plant (BoP), including rectifiers, cooling systems and gas processing.

The stack represents 40–50% of total system costs in both PEM and alkaline electrolysers, while BoP components can make up 50–60%. Cost estimates for AEM and solid oxide electrolysers remain unclear due to their low commercialisation levels and lack of large-scale deployment. However, studies suggest that past cost reductions have been more pronounced for PEM electrolysers, with significant cost variability, ranging from USD 306/kWh to USD 4,748/kWh, highlighting the complexity of benchmarking electrolyser costs (IRENA, 2021a).

Future cost reductions will depend on scaling up production, innovation in stack design, and reducing the cost of key components such as power supplies and bipolar plates (IRENA, 2024d).

Mitigation and net zero potential

Green hydrogen can play a crucial role in reaching climate goals through its capacity to link renewable energy and hard-to-abate sectors such as industry or shipping. Its role as an energy carrier and storage system enables the decarbonisation of remote applications that are far from electricity grids.

Moreover, like other storage options, green hydrogen plays an important system-wide role, providing additional longer-term flexibility to storage and electricity generation.

The transition from carbon-based energy sources to clean, low-carbon alternatives is essential to achieving global carbon neutrality goals, such as limiting temperature rise to 1.5°C. Hydrogen's unique characteristics make it a key enabler in this transition, offering long-term energy storage, industrial decarbonisation and transport solutions.

Despite its potential to reduce emissions, particularly in hard-to-abate sectors like steel, cement and chemicals, some barriers still hinder hydrogen's large-scale adoption. High production costs, especially for green hydrogen from electrolysis, remain a major challenge due to the expensive electrolyser technology and renewable electricity requirements. Additionally, there is a lack of hydrogen infrastructure, including pipelines, storage facilities and refuelling stations, that is further slowing down deployment (IRENA, 2024d). Achieving cost reductions will require substantial investments in research and development, as well as in infrastructure development and policy support, such as carbon pricing, renewable energy incentives and regulations promoting hydrogen adoption. Furthermore, the sustainability of hydrogen depends on its source – for instance, hydrogen from natural gas with CCS may still result in carbon emissions, and hydrogen from biomass could raise land-use concerns. While the hydrogen economy is promising, overcoming these economic, technical and regulatory hurdles is crucial to realising its net zero potential by 2050.

Just Transition aspects

A Just Transition driven by green hydrogen has the potential to generate economic opportunities, particularly in developing countries with high renewable energy potential. Due to its capital and technology-intensive nature, green hydrogen technologies require highly specialised professionals, making job creation more challenging than it is for modular technologies like solar energy (UNIDO, 2024). To maximise these employment options, education and training programmes should be designed to prepare members of the community, including women and young people, to join the workforce. Reskilling workers from fossil fuel industries would also help ensure an equitable transition. More specifically, workers from the natural gas industry may be well suited for specialised jobs in green hydrogen production. In view of the potential challenges regarding employment options, introducing benefit-sharing mechanisms to guarantee a fair distribution of profits from green hydrogen investment becomes crucial. Capturing additional benefits from investors may be possible by establishing mandatory financing of community development, and from tax revenues by providing direct payments to citizens via tax revenues from green hydrogen production, exports and leasing public land. Civil society and local communities must be included in decision-making, to identify the most effective revenue sharing interventions.

Green hydrogen production is an energy-intensive process, however, many of the locations where it is produced lack universal energy access. The construction of green hydrogen facilities and its related energy infrastructure, present a valuable opportunity for the installations to account for the energy demands of local populations and improve their energy access. In a similar manner, electrolysers require vast amounts of water. This is particularly concerning for countries or areas that face water scarcity. Identifying sites where water use for green hydrogen production does not threaten local communities' access to drinking water or agricultural needs should be prioritised.

Barriers to dissemination / deployment

Despite its potential to drive decarbonisation and economic growth, green hydrogen faces several barriers to large-scale deployment. These challenges span technological immaturity, energy losses, infrastructure limitations, economic viability, policy gaps and social acceptance. Addressing these barriers is crucial to ensuring that green hydrogen can become a cost-effective and safe energy carrier in the global transition to net zero emissions. Below are some of the key obstacles that must be overcome to scale up green hydrogen deployment effectively (IRENA, 2021a):

- Immaturity of hydrogen technologies at scale: some hydrogen technologies such as small-scale electrolysis are already mature. Others, such as large-scale electrolysis, hydrogen shipping and synthetic fuel production, are still in development. Key components for these technologies remain at the prototype stage, and larger-scale deployments have yet to be fully tested, which makes financing and insuring these technologies more daunting.
- Energy and hydrogen losses across the value chain: green hydrogen production, transportation, storage and use suffer from efficiency losses at multiple stages. A typical electrolyser efficiency is usually at around 66%, meaning 1.5 MWh of electricity is required to produce 1 MWh of hydrogen (IRENA, 2021a). Moreover, hydrogen storage and transportation present significant challenges due to hydrogen's low volumetric energy density and tendency to permeate metal-based materials. Various physical storage methods include compressed gas storage (200–700 bar), cryogenic liquid hydrogen (-253°C), and cryo-compressed hydrogen – each offering different trade-offs between storage density, energy losses and infrastructure costs. Compressed hydrogen storage is widely used but requires high-strength pressure vessels and has limitations related to cost and capacity, whereas liquid hydrogen storage, despite its higher density, suffers from energy losses of up to 40%.
- Safety concerns and handling complexities: hydrogen is highly flammable and ignites more easily than conventional fuels, which requires strict safety protocols and comprehensive training programmes to ensure safe handling, all of which increase costs and operational complexity.
- High costs along the entire hydrogen value chain: green hydrogen production remains expensive, with costs ranging from USD 4.5/kg to USD 12/kg in 2023 – up to four times the price of grey hydrogen. Additional conversion, storage and transport costs further increase expenses, with compression adding USD 1–1.5/kg, liquefaction USD 2–3/kg, and ammonia conversion USD 0.4–0.9/kg, making long-distance hydrogen trade economically challenging.
- Shortage of skilled personnel and expertise: the hydrogen sector requires a highly trained workforce for system design, implementation, maintenance, regulatory development and project management.
- Regulatory and policy gaps: the hydrogen sector lacks a unified regulatory framework, which generates inconsistencies in safety standards, licenses

and permits, and incentives across different regions. Many hydrogen projects are stalled due to permitting delays and fragmented government coordination, and the absence of clear policy roadmaps guiding long-term investments.

Solutions in the real world

The Poza de la Sal diapir in northern Spain has been identified as a promising site for large-scale underground storage of green hydrogen, utilising surplus wind energy from the a nearby wind park. The geological characteristics of the salt cavern, including low permeability, low porosity and minimal seismic activity, provide optimal conditions for safe hydrogen containment. The proposed storage design involves the controlled leaching of salt to form a stable cavern and to ensure structural integrity while allowing for seasonal energy storage. (Olmedo, 2022). The project aligns with Spain's broader decarbonisation goals by replacing grey hydrogen, which currently dominates in the industrial sector, with green hydrogen produced via electrolysis powered by renewable electricity. Additionally, given Spain's high wind energy capacity accounting for 22% of total installed power capacity and 23% of power generation in 2023 the cavern system offers a strategic solution for balancing energy supply and demand, particularly as onshore wind power capacity is projected to grow at a compound annual growth rate of 6% from 2023 to 2035.

Beyond its energy storage capabilities, the project presented several technical and environmental challenges, which required careful engineering to the stability of the cavern and to prevent hydrogen losses. Safety protocols will be crucial in the future, particularly to manage gas pressure and to mitigate risks associated with cavern deformation. The facility's integration with hydrogen transportation networks, either through blending with natural gas or direct use in industrial and mobility sectors, highlights its role in enhancing Spain's hydrogen economy.

Furthermore, the potential expansion to a dual-cavern system could store close to 800 GWh increasing storage capacity to accommodate growing renewable energy surpluses. As onshore wind power is expected to continue expanding, the hydrogen storage facility at Poza de la Sal will play an important role in ensuring the efficient use of renewable resources.

3.3 Energy transmission and distribution

Integrating renewable energy technologies into the grid, especially the variable kind, will require adopting innovative approaches to the management of the system. This is because the electricity production profile of solar PV, when coupled with a typical load curve of a centralised electricity system using predominantly thermal generating capacity, draws what is now typically recognised as a 'duck curve' shape.

The duck curve was first introduced by the California Independent System Operator in 2013 and is now synonymous with the challenges brought by increasing rates of solar PV. The curve shows generation from the utility dropping during the middle hours of the afternoon. This occurs because this is the moment of peak generation from distributed solar PV systems, which decreases the need for electricity generation from the grid. As solar PV power supply wanes in the later afternoon and in the early evening, the utility must rapidly ramp up production to make up for it, generating wear and tear to the system. Wind resources, despite drawing a different daily generation curve, pose a similar type of problem.

The integration of renewable energy resources into the grid, together with the drastic expansion of electricity in the energy mix, will be necessary prerequisites to reach net zero by 2050. According to the IEA, electricity generation will need to reach net zero emissions before 2045, with renewables amounting to nearly 90% of generation in 2050 and electricity reaching more than 50% of total final energy consumption in the same year (IEA, 2023b).

This means that the grid will have to modernise, adapt and integrate storage systems to reduce wear and tear and to readily release electricity when it is needed, preventing blackouts or curtailments.

One of the key requirements for an electricity grid going through the changes described above is that it be flexible. This means that the system must be able to withstand rapid changes in net load and adjust supply accordingly; it must be able for demand to adjust rapidly to supply, and it must be able to ensure that storage options quickly cover the gaps between supply and demand. Moreover, transmission and distribution lines must be equipped with technology that allows for greater energy efficiency and for a greater resilience of transmission and distribution systems. This will become even more important as weather patterns and temperatures are altered by climate change.[6] This guidebook provides an overview of the key technologies that can be applied along the grid system, from transmission to substation to distribution level, in order to adapt them to the challenges that will arise in the future.

3.3.1 Dynamic line ratings (DLR)

Transmission lines can carry a specific amount of current at a given temperature. This maximum current rating is called ampacity, and can be influenced by physical and electrical factors (properties of the material being used, insulation, line current) as well as external factors (air temperature, wind speeds, solar radiation). System operators had traditionally been using estimates of meteorological conditions to calculate a theoretical ampacity that fail, however, to take into account varying weather conditions. DLR systems can vary the thermal capacity of transmission cables dynamically and in real time, and have shown to increase line capacities in ranges from 10 to 25% in different locations. Moreover, they can provide congestion relief by forecasting expected transmission capacities with greater accuracy, as well as generating greater asset awareness by utilities, who are more likely to perform timely maintenance and to more accurately assess the health and lifetime of infrastructure (IRENA, 2020a).

DLR systems will usually consist of a set of sensors, a communication system to relay information back to the control room, and a DLR analytics engine to analyse weather and temperature data. A successful implementation of these technologies, however, requires more than just data – rapid communication to decision makers is essential and this can be done via radio, cellular networks, satellite or fibre optics.

Some obstacles exist in the application of these technologies (US Department of Energy, 2021):

- Economics: installation costs have been signalled by some transmission operators as potential blockers.
- Data accuracy: inaccuracies can still occur in the data provided by DLR systems due to measurement or modelling errors.
- Know-how: installing and operating DLR systems requires operational knowledge and time for operators to adapt.

3.3.2 Power flow controllers (PFC)

These types of equipment (actuators and hardware solutions) focus on improving the physical capability of grid infrastructure by changing the way in which currents flow through transmission systems without making changes to the topology of the system itself or the generator dispatch. They are more capital intensive than optimising software solutions, and can be subdivided into technologies for alternating current (AC) and direct current (DC):

Alternating current PFC

The flow of power through an AC transmission line is determined by voltage at the sending and receiving points of a line, plus the reactance of the line and the difference in the phase angles between the sending and receiving ends of the line. Unified power flow controllers (UPFCs) are one of the most advanced and versatile devices in the Flexible AC Transmission System (FACTS) family. They are used in power systems to control these four variables in order to enhance stability and optimise the use of transmission networks. Recently, institutions such as the US Department of Energy have been encouraging the deployment of modular devices (Distributed Series Reactor – DSR) that can be installed along different transmission lines rather than at substation level (US Department of Energy, 2021).

AC PFC technologies enhance power transfer capability, improve voltage profiles and stability, mitigate power oscillations, and provide high flexibility and control over power flows in transmission systems.

Direct current PFC

DC power flow control is more complex and expensive than AC PFC but offers greater flexibility and efficiency, especially for long-distance power transmission and renewable energy integration. Early DC PFC systems relied on technologies enabling point-to-point

6 In this guidebook we will concern ourselves mainly with supply-side and operational flexibility. Demand-side flexibility may be covered in further guidebooks focusing more on end-user electricity consumption.

transmission between AC grids. However, technological advances have introduced more adaptable and stable power flow control. Unlike traditional AC grids, this allows grids to operate asynchronously, preventing cascading failures and enhancing grid resilience. These systems have gained attention in recent years, especially for connecting offshore wind farms and large solar power plants to the grid. These systems offer frequency support, power sharing and optimised renewable energy integration, making them essential for a modern, efficient and renewable-powered energy grid.

3.3.3 Topology optimisation

The electric grid has traditionally been seen as a system that has to operate in its entirety all the time. However, experience has shown that optimising grid usage through localised and temporary line switch-offs can result in less expensive and more reliable power flows. While DLR operates on a single line, topology optimisation is a systems-level approach that allows to optimise the grid's layout for a given set of loads in order to minimise line congestion. The benefits from grid topology optimisation are numerous and range from improving operational challenges, to generating savings by deferring infrastructure investments.

To accurately assess the impact of grid topology optimisation, operators use digital twin models, which allow for simulation and analysis of different grid configurations before implementing them in real-world operations. While the term digital twin may suggest purely computer-based simulations, these models often involve physical hardware components operating in real-time through hardware-in-the-loop (HIL) simulations. Advanced HIL platforms, such as Opal-RT machines, enable real-time digital twin simulations by connecting with Remote Terminal Units (RTUs) – such as the Orion Grid Automation solution – or other grid automation equipment. These setups safely test grid responses to different scenarios, validate optimisation strategies and refine system controls without risking real-world disruptions. By combining AI-driven analytics, real-time data processing and hardware-integrated simulations, grid operators can ensure a more resilient, adaptive and intelligent energy network capable of handling the increasing complexity of modern power systems. Challenges in the adoption of this technology have surfaced and can be summarised as follows (US Department of Energy, 2021):

- Model size: the larger the grid system, the more complicated and costly it will become to apply topology optimisation. Models and equipment that can successfully manage very complex grid systems are costly to run, or would require high-performance computing to reduce computation time.
- Data accuracy: data simplifications are necessary to run a complicated grid system efficiently and in a limited amount of time. This will, however, require developing algorithms that allow operators to make decisions more confidently and more accurately.
- Impacts on physical infrastructure: the dynamic optimisation of a grid system can exert strains on grid components, accelerating wear and tear.

3.3.4 Advanced Distribution Management Systems (ADMS):

These technologies refer to the use of smart equipment like sensors, automated switches and controllers that can detect problems at the distribution level and automatically reroute electricity in order to reduce the amount of people losing power. They operate by using switches to automatically isolate affected areas, allowing operators to control and monitor the devices from a distance.

Key functions of ADMSs are to detect faults and isolate the specific section of interest, reroute power to other lines, keep distribution voltages within range and working with other complementary technologies (see below), balance loads to different feeders to prevent overloads, and gather real-time data to help utilities spot trends, plan maintenance and respond quickly to events.

The crucial benefits of these technologies depend on improved reliability of the system at the distribution level, cutting down the duration and extent of outages, and allowing customers to experience fewer and shorter outages. Efficiency gains are also to be observed – automatic adjustments of network configuration and voltage minimise energy losses and optimise system performance. Finally, they allow for fewer field dispatches reducing costs, and allow for a better integration of renewables such as distributed PV and wind turbines.

3.3.5 Conservation voltage reduction (CVR) and voltage/VAR optimisation (VVO)

At the distribution level, conservation voltage reduction (CVR) and voltage/VAR optimisation (VVO) provide additional efficiency options. In CVR, electricity is delivered to end consumers within an acceptable voltage range. Typically, delivering electricity at the lower end of the voltage range can result in energy savings for the consumer, as many types of equipment operate more efficiently at lower voltage volumes. Conservation voltage reduction technologies allow for distribution system operators to regulate and stabilize voltages on that lower end of the spectrum. This allows for energy savings at the consumer end, since many appliances consume less power at slightly lower voltages. It also allows for a reduced carbon footprint from less fuel burned in power plants, which can also translate into savings. All of this can be obtained at a minimum impact to the consumer, with most end-users not realising the slight reduction in voltage.

Voltage/VAR optimisation systems not only manage voltage, but also manage the reactive power (VAR) present in distribution systems. This is the portion of electricity supporting magnetic fields in motion and transformers. Sensors and smart metres track power quality at different points in the feeder, and cut down excessive reactive power flow, increasing the carrying capacity of distribution lines and therefore cutting down on wasted energy and keeping voltages consistent across the network (Wang, Z., 2019). The benefits from this technology are reduced energy losses, enhanced power quality by regulating voltage and avoiding flickering or dips, and lowering operating costs by postponing necessary upgrades on infrastructure.

3.3.6 Mini-grids

Mini-grids are small-scale electrical systems that can operate either connected to the main grid, or independently. These systems contain local energy generation, which can be from renewable energy sources such as solar PV, wind turbines or small hydro, that are coupled with storage systems such as batteries or, also commonly, small-scale pumped hydro. In normal conditions, they can operate in grid-connected mode, importing extra power or sending surplus (ideally renewable) electricity back to the grid.

Mini-grids can also operate disconnected from the main grid, allowing for electricity generation during major outages by disconnecting automatically from the main grid. Benefits from these distribution systems amount to an enhanced resilience of the system, especially for critical infrastructure such as hospitals or in disaster-prone regions. They can also facilitate and accelerate the adoption of local renewable energy sources, allowing for smaller-scale generation investments where they are needed. Finally, they can create economic opportunities for local communities, by allowing them to sell excess power back into the grid.

Technological innovations are also solving older problems that pre-date variable renewable energy and distributed generation. For instance, trapezoidal aluminium strands in electricity cables, together with carbon fibre replacing steel reinforcements, can reduce electricity losses along the grid, alongside new materials used in transformers (such as amorphous metals instead of steel).

Economic assessment and affordability

Deployment costs for the technologies described above can vary dramatically and can be difficult to estimate. In the case of dynamic line rating systems, an installation of DLR sensors across transmission lines in the US states of Indiana and Ohio resulted in an approximate cost of USD 45,000 per mile, increasing grid capacity by 50%. The whole operation took nine months (Centre for Energy and Environmental Policy Research, 2024).

These technologies can result in substantial economic savings. Power flow controllers deployed on the UK National Grid resulted in 1.5 GW of capacity enhancement and in approximate savings of USD 500 million (Centre for Energy and Environmental Policy Research, 2024). At the same time, other projects revealed costs ranging from USD 1.5 million to USD 5.2 million. (US Department of Energy, 2020).

Mitigation and net zero potential

Each of these technologies contributes in a unique way towards mitigation and net zero potential goals. Dynamic line ratings, for example, reduce the need for new transmission infrastructure by maximising the use of existing transmission lines, which in turn contributes to lower carbon emissions. Advanced power flow controllers, on the other hand, reduce transmission losses by better managing congestion and distributing electricity more efficiently, which means less electricity needs to be generated. By reconfiguring the grid and improving power flows, topology optimisation can induce the reliance on less efficient energy generation sources, while ADMS, CVR and voltage/VAR optimisation systems can reduce outages through real-time monitoring, as well as reduce energy demand by optimising voltage and reactive power, thus reducing unnecessary generation. Finally, mini-grids reduce dependency on diesel generators to reach more remote areas.

Overall, these technologies dramatically improve the efficiency of the grid and consumer demand, indirectly reducing electricity generation and the need for new infrastructure. Moreover, they facilitate the integration of renewable energy in the grid, which is in and of itself the greatest contribution towards achieving net zero.

Just Transition aspects

Mini-grids play an undisputed role in enhancing Just Transitions. By expanding energy access to remote communities, they enable the emergence and expansion of productive activities that contribute to the creation of employment, to the expansion of economic wealth and to the improvement of livelihoods. Mini-grids play a special role in improving the life of women giving birth in hitherto unelectrified health clinics, or in allowing for the preservation of the vaccine cold chain, improving the health of communities that find themselves very far from the grid. Moreover, building and maintaining a mini-grid often requires the use of a local workforce, in itself generating employment opportunities.

Enhancing climate resilience of energy technologies

To face the growing disruptions caused by climate change, transmission and distribution, grids will have to adopt technologies to strengthen their resilience along the following axes:

1) Improving outage response time: outages are to become more frequent together with extreme climate events;
2) Improving their capacity and resilience as temperatures rise;
3) Improving their physical durability to withstand extreme climate events.

Many of the technologies described above already ensure that resilience can be improved among some of these intervention axes.

1) **Improving outage response time:** ADMS provide real-time monitoring and can automatically restore outages, power flow controllers redirect power flows when transmission lines are damaged or congested, and topology optimisation can reroute power away from damaged sections. Mini-grids, at the same time, can operate independently of the main grid and can continue supplying electricity when this fails.
2) **Improving grid capacity and resilience as temperatures rise**: Dynamic line ratings use real-time weather data to examine the real capacity of transmission lines and increase power flows without these overheating. CVR and VVO, at the same time, lower grid demand affecting distribution networks, which can reduce stress on the grid during heatwaves.

There is a wide spectrum of technologies that can be deployed to improve the reliability of the grid through the third axis of intervention: **improving the physical durability of the grid to withstand extreme climate events.**

Such technologies, or methods, include:

- Undergrounding power lines to protect them from exposure to wind, ice or fire hazards;
- Reinforcing infrastructure components by strengthening substations, transformers and switchgears with robust materials and foundations, to prevent failures;
- Managing surrounding vegetation, which prevents outages caused by falling trees and falling tree branches;
- Replacing ageing poles, using materials such as steel, fibreglass or reinforced concrete;
- Improving cable resilience, by using armoured external cables, sheaths made from polyvinylchloride or silicone rubber to resist high temperatures, or special cold temperature cable applications.

Barriers to dissemination / deployment

The section before outlined many of the technologies used to adapt the grid system to variable renewable energy, both in transmission and distribution. This section will strive to display potential barriers in deploying such technologies (see Table 3).

Solutions in the real world

These solutions have been implemented in different ways and in different locations with increasing success. Some examples are presented in Table 4.

Table 3: Potential barriers in deploying energy transmission and distribution technologies

Technology type	Implementation challenge
Dynamic Line Ratings (DLR)	The deployment of DLRs must be calibrated to minimise wear and tear on other equipment on the grid. With increased capacity, other components may wear out faster and their lifespan could be shortened. Clear guidelines must also be put in place to ensure that DLR respects best practices and standards to address cybersecurity concerns and ensure interoperability of real-time sensors, data collection mechanisms and smart grid technologies on which DLR systems rely (US Department of Energy, 2019).
Power Flow Controllers (PFC)	These technologies are generally more capital intensive than sensor and software solutions (US Department of Energy, 2020.)
Topology Optimisation	Topology optimisation relies on real-time simulations and adjustments, and its implementation is not straightforward, requiring advanced software tools (US Department of Energy, 2020). The application also requires an in-depth understanding of the constraints affecting the grid system and will require high levels of coordination (Applied Energy Services, 2024).
Advanced Distribution Management Systems (ADMS)	These tools require extensive modelling and data requirements. These systems will require specialised training for personnel such as operators or planners (Oracle, 2022).
Conservation Voltage Reduction (CVR)	CVR may require advanced equipment, as utilities will need to invest in advanced voltage regulation and control equipment (Stern et al., 2015). Measuring the benefits of CVR solutions may be challenging and resource-intensive for utilities, since estimating potential customer savings from changes in voltage requires a sizeable amount of load and voltage data (US Environmental Protection Agency, 2017). CVR must be standardised with other voltage control tools, which may be challenging (Khodaei et al., 2020).
Voltage/VAR Optimisation (VVO)	A lack of coordination between voltage and VAR control systems can reduce the effectiveness of these tools (Electric Power Research Institute). These tools require compatibility with existing grid infrastructure, which may include technologies that are outdated (Dizdar et al., 2023).
Mini-grids	Countries must put in place clear regulations to protect mini-grid investments, especially when this concerns the arrival of the main grid that could make the investment void (SEforAll, 2020). Other challenges such as financial may arise – serving low-income rural customers with variable incomes poses risks to revenue collection (SEforAll, 2020).

Table 4: Real world examples from deploying energy transmission and distribution technologies

Technology type	Real-world examples
Dynamic Line Ratings (DLR)	Line Vision, PJM and American Electric Power (AEP) implemented DLR and avoided congestion costs on an 18-mile stretch, resulting in annual congestion savings of USD 4 million per year. Other examples have meanwhile reported a capacity increase between 6 and 30% for 83% of the observed time (US Department of Energy, 2020).
Power Flow Controllers (PFC)	In 2021, the UK National Grid deployed 48 advanced power flow control devices across its network. This initiative unlocked 1.5 GW of additional capacity, leading to estimated savings of $500 (MIT CEEPR, 2024).
Topology Optimisation	The Electricity Reliability Council of Texas (ERCOT) used topology optimisation tools to reconfigure its system more dynamically, reducing congestion and enhancing the reliability of electricity delivery (Ruiz, 2017).
Advanced Distribution Management Systems (ADMS)	Tata Power – Delhi Distribution Limited implemented ADMS technologies, leading to improved operational efficiency (GBCI, 2018).
Conservation Voltage Reduction (CVR) / Voltage/VAR Optimisation (VVO)	A comprehensive study on the impact of CVR and VVO on individual and commercial loads has revealed that these technologies allow a reduction in energy consumption, showing a potential of 0.5–3% reduction (Alzubi et al., 2025).
Micro-grids	The Mbogo Valley Tea Factory in Kenya implemented a DC-coupled solar microgrid with battery storage, reducing reliance on costly diesel (previously $0.40 per kWh), improving power reliability by eliminating 2–4 daily outages lasting 1–6 hours, and preventing product loss due to grid failures (Microgrid Knowledge, 2022).

4. Conclusions

Photo: UNIDO, Envato

The transition to renewable energy is a critical step for developing countries aiming to reduce GHG emissions, secure energy independence and ensure sustainable economic growth. However, achieving this transition while minimising negative effects on employment and disruptions to local communities requires a strategic and well-balanced approach, which has been considered overall throughout the guidebook. It is the role of decision makers, and their advisors, in this context to weigh multiple factors, including the technological suitability of different renewable resources, the adaptability of the grid infrastructure, financing constraints and socioeconomic implications, aligning national priorities with international climate commitments while ensuring equitable access to clean energy.

A balanced renewable energy strategy incorporates ideally a diverse mix of energy sources, ensuring stability and complementarity in generation. Solar PV and wind energy have seen dramatic cost declines and have become the dominant renewable energy technologies globally. However, their intermittency necessitates integration with flexible and dispatchable energy sources. Hydropower, where geographically feasible, offers a reliable baseload supply and storage potential through pumped hydro, but it must adapt to increased flexibility requirements by improving turbine design. Biomass and geothermal can provide stable generation capacity, particularly in rural or industrial settings where decentralised solutions are preferred. Biomass must ensure that energy crops are cultivated locally and that they do not encroach on food crops. Marine energy, while promising, remains at a nascent stage and is not yet commercially viable for large-scale deployment in most developing contexts, but could become a solution in island settings. Technological developments should be keenly observed in the coming years.

The optimal mix can moreover be tailored to local resource availability, in an ideal scenario. Countries with abundant sunlight can therefore prioritize solar PV, complemented by wind where conditions allow, and supported by extensive capacity building efforts especially for off-grid installations in remote areas. Hydropower and biomass can serve as stabilising forces in the energy mix, ensuring a continuous power supply. Enhanced geothermal systems can be explored in regions with geothermal potential, offering both electricity and industrial heat applications. Expanding regional collaboration and integrating interconnections with neighbouring countries can further balance supply and demand, allowing for greater energy security and economic efficiency.

The guidebook also identifies grid modernisation's potential to accommodate increasing shares of renewable energy while ensuring reliability. This can be done by investing in transmission and distribution infrastructure to prioritize flexibility, efficiency and resilience. Advanced Distribution Management Systems (ADMS) and conservation voltage reduction (CVR) can enhance operational efficiency, minimise energy losses and optimise power delivery. Dynamic line ratings (DLR) and power flow controllers (PFCs) allow for real-time grid adjustments, reducing congestion and improving stability.

Storage solutions can complement intermittent energy sources. Pumped hydro remains the most cost-effective, utility-scale storage option, particularly in countries with suitable topography. Battery storage, particularly lithium-ion and emerging sodium-ion technologies, can facilitate grid stability by providing rapid response and peak demand management. In regions with significant solar resources, concentrated solar power (CSP) with thermal storage can ensure power availability after sunset. Green hydrogen, while still in early development, presents a long-term opportunity for energy storage and industrial applications, especially in sectors such as transportation and manufacturing. Integrating these storage technologies with smart grid innovations can greatly enhance energy dispatch flexibility and grid stability.

A significant increase in renewable energy investment requires long-term financial planning, particularly where capital costs and financing risks remain high. Lowering the weighted average cost of capital (WACC) is crucial for attracting private sector participation. Policymakers may consider public-private partnerships (PPPs), green bonds and concessional financing from multilateral development banks to accelerate deployment. Establishing stable regulatory frameworks, clear permitting processes and competitive auction mechanisms can further enhance investor confidence.

Supply-chain constraints can be addressed by developing local manufacturing capacity for renewable energy components, such as solar panels, wind turbines and battery systems, can reduce import dependency while creating new economic opportunities. Strengthening regional energy markets and cross-border electricity trade can further optimise generation costs and improve system resilience. Additionally, governments can inventivise technological innovation through tax credits and subsidies for research in emerging renewable energy solutions.

One of the primary benefits that can arise from renewable energy technologies is their potentially positive impact on employment, if deployed carefully and correctly. Strategic workforce retraining programmes can facilitate skill transfer from coal, oil and gas industries to renewable energy sectors. Geothermal energy, offshore wind and battery manufacturing share technical overlaps with fossil fuel industries and provide promising re-employment pathways. Governments could inventivise renewable energy companies to prioritise local hiring, integrating vocational training programmes that align with industry needs.

Microgrids and distributed renewable energy systems can create localised economic benefits, particularly in rural areas. Community-owned energy projects ensure that profits stay within the local economy while expanding energy access. Strengthening local supply chains and manufacturing hubs for renewable energy infrastructure can provide long-term employment stability, ensuring that economic benefits extend beyond initial construction phases. Governments can further support Just Transition strategies by promoting labour rights protections and equitable wage structures in renewable energy sectors.

The deployment of renewable energy should be socially inclusive and not disruptive to workers' livelihoods or local communities. While large-scale solar and wind projects may generate issues related to conflicts over land use, particularly in regions where agriculture is a primary livelihood, rising efficiency rates could improve this situation. At the same time agrivoltaics, combining solar PV with agricultural activities, can mitigate land competition while improving productivity. Hydropower projects, should be informed by comprehensive social impact assessments to prevent potential community displacement and damages to livelihoods and economic activity. Though more efficient recycling practices are being utilised to improve treatment of waste originating from renewable energy systems, countries are advised to carefully consider sustainable treatment options when adopting these solutions.

Engaging workers and local communities from the planning stage is can secure social acceptance. Participatory decision-making, community benefit-sharing mechanisms and revenue-sharing models can align renewable energy deployment with local priorities. Moreover, proactive policies can ensure that human rights and labour protections are upheld across the renewable energy supply chain. Addressing gender equality in energy access and employment can contribute to ensuring the energy transition benefits all segments of society. Capacity building initiatives should accompany the deployment of renewable energy technologies, to support skills transitioning as well to ensure the long-term financial and technical viability of systems deployed in more remote areas. Finally, in spite of drastic cost reductions in the technologies being described in the guidebook, some communities in more isolated settings may require support to afford the upfront costs.

For developing countries, transitioning to renewable energy can be an inestimable opportunity. A diversified, well-integrated energy mix – supported by modernised grids, robust storage solutions and investment-friendly policies – can enhance energy security, drive economic growth and create sustainable employment opportunities. By adopting flexible market mechanisms, regional cooperation and inclusive development strategies, policymakers can accelerate the energy transition while ensuring equitable socioeconomic benefits, while closely aligning national climate and development agendas to pursue energy transition goals.

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Photo: UNIDO, Envato

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6. Appendices

Photo: UNIDO, Envato

Appendix I: Summary sheets: mitigation technologies and practices

Solar PV

Technology description

Solar photovoltaic (PV) technology converts sunlight into electricity using semiconducting materials that move electrons when exposed to light. Most PV cells are made from silicon, with two layers doped with boron and phosphorus to create an electric field. When photons hit the cell, electrons are displaced, generating electricity. Panels feature an anti-reflective coating to maximise absorption. PV technology includes monocrystalline, polycrystalline, thin-film and concentrated PV systems, each differing in efficiency, cost and applications.

Technology advantages for net zero and Just Transition

Solar PV is key to decarbonisation, with the IEA projecting 7,000 GW of installed capacity needed by 2030 to meet net zero goals (IEA, 2024d). In 2023, solar PV accounted for 73% of new renewable energy additions and plays a critical role in electrification, especially in underserved regions. Its modularity enables deployment from large-scale plants to mini-grids and standalone systems. Advances like bifacial modules and perovskite cells enhance efficiency, expanding solar's competitiveness.

From a Just Transition perspective, solar PV creates jobs and drives economic growth in fossil fuel-dependent regions. Policies that support local manufacturing, workforce training and equitable energy access can maximise benefits. However, challenges include precarious labour conditions, land use conflicts and affordability concerns. Governments should implement strategies to support displaced workers, involve communities in decision-making and ensure fair energy access.

Technology costs

Solar PV has seen a 90% cost decline in utility-scale projects since 2010, driven by lower manufacturing costs and improved efficiency. However, capital costs vary by region, largely due to financing conditions. Developed markets like France and the USA have lower financing costs than emerging economies such as Egypt and Morocco, where investment risks are higher. Solutions like credit guarantees, green bonds and tax incentives can help reduce financial barriers and attract investments.

Technology considerations and vulnerabilities

Solar PV faces challenges, including grid flexibility issues, due to its intermittent nature, requiring strong transmission infrastructure and storage. Large-scale solar farms compete for land, but agrivoltaics and floating PV help mitigate this. Climate change may impact PV performance, with rising temperatures, extreme weather and wildfires reducing efficiency. More resilient panel designs, advanced cooling and improved recycling processes are essential to maintaining solar's long-term sustainability.

Wind

Technology description

Wind power generates electricity by converting wind energy into mechanical motion that drives a turbine. Traditional gear-driven systems require maintenance due to wear and tear, while direct-drive systems, which use larger generators, eliminate the need for gearboxes. Wind power is harnessed through both onshore and offshore facilities, with offshore wind exhibiting higher capacity factors and energy output.

Technology advantages for net zero and Just Transition

Wind power plays a crucial role in the energy transition, with onshore and offshore wind capacity growing rapidly due to declining costs. Onshore wind is among the cheapest sources of electricity, while offshore wind, particularly floating systems, enables deployment in deeper waters with stronger, more consistent winds. Offshore wind's ability to generate power at night complements solar PV, enhancing grid stability. The integration of wind and solar can reduce reliance on storage technologies while ensuring more reliable renewable energy supply.

From a Just Transition perspective, wind energy creates significant employment in manufacturing, installation and maintenance. Offshore wind can revitalise coastal economies by supporting jobs in shipbuilding and marine logistics. However, wind energy development must address concerns about fair labour practices, displacement of communities and environmental impacts. Proper siting of onshore wind farms is necessary to protect bird and bat populations, whereas offshore wind projects must consider fishing rights and marine biodiversity. Policy measures should ensure community benefits, fair employment standards and equitable participation in wind energy expansion.

Technology costs

Wind power has seen dramatic cost reductions, with levelised costs of electricity (LCOE) falling by 70% for onshore and 63% for offshore wind since 2010. Onshore wind remains the most cost-effective mature renewable energy source, though offshore wind remains more expensive due to challenging installation and maintenance environments. Floating offshore wind, while promising, has high capital costs. Financing costs vary by region, with emerging economies facing higher borrowing rates, which can slow deployment. Supply chain risks, particularly for rare earth minerals, could impact future costs and manufacturing stability.

Technology considerations and vulnerabilities

Wind energy faces challenges related to intermittency, requiring grid modernisation and storage solutions. Offshore wind is more consistent but comes with high maintenance costs due to corrosion and harsh marine environments. Climate change may impact wind resources, with rising temperatures reducing air density and wind speeds, while extreme storms pose risks to turbine infrastructure. Adaptations such as resilient turbine materials, improved siting and enhanced grid integration will be necessary. Additionally, geopolitical tensions could disrupt rare earth material supply chains, affecting the production of wind turbine generators.

Hydropower

Technology description

Hydropower generates electricity by using flowing water to spin a turbine, typically from an artificial reservoir created by a dam. Other types include run-of-river systems, which divert water through a powerhouse before returning it downstream. Hydropower is categorised into large-scale (over 100 MW) and small-scale (under 10 MW), with small-scale projects often used for energy access in mini-grids. Pumped storage hydropower (PSH) provides efficient energy storage by shifting water between two reservoirs at different altitudes, balancing grid demand and supply.

Technology advantages for net zero and Just Transition

Hydropower plays a crucial role in stabilising grids with high shares of intermittent renewables. Its ability to provide frequency regulation and peak power support makes it complementary to solar and wind. However, ageing infrastructure – 40% of global hydropower plants are over 40 years old – requires modernisation with variable-speed turbines and digital monitoring systems. Integrating hydropower with solar PV or wind through hybrid systems can improve efficiency and land use while reducing wear on hydroelectric infrastructure.

Hydropower supports a Just Transition by providing employment across engineering, construction and maintenance. Small-scale hydropower, in particular, boosts local economic development and job creation. However, large hydro projects can displace communities, disrupt ecosystems and create geopolitical tensions over water resources. Careful planning, inclusive decision-making and fair compensation are essential to ensuring equitable benefits and minimising negative social and environmental impacts.

Technology costs

Unlike solar PV and wind, hydropower costs have risen, with levelised costs of electricity (LCOE) 33% higher in 2023 than in 2010. Large hydro projects require extensive civil engineering works, long development timelines and high capital investment, often taking up to 10 years to complete. Small hydro, while generally cheaper, can face significant infrastructure costs depending on terrain complexity. Financing remains a key challenge, particularly in developing economies, where high upfront costs and lengthy permitting processes deter investment.

Technology considerations and vulnerabilities

Hydropower's reliance on stable water availability makes it vulnerable to climate change. Altered rainfall patterns and prolonged droughts can reduce output, while extreme weather events may damage infrastructure. Solutions include expanding reservoir capacity, upgrading turbines for variable water flow and integrating AI-driven water management systems. Large dams can emit methane from decomposing organic matter, but emissions remain lower than fossil fuel-based generation. Sustainable reservoir management can further reduce this impact, ensuring hydropower remains a viable and resilient renewable energy source.

Biomass

Technology description

Biomass energy is derived from organic materials such as wood, agricultural residues, municipal waste and algae to produce electricity. These materials can be burned directly to generate steam for turbines or processed into biogas and biomethane through thermochemical conversion. Biomethane, produced by heating biomass in oxygen-free chambers, can serve as a renewable gas for power generation. Biomass is classified as renewable since it releases CO_2 previously absorbed during plant growth, though its carbon neutrality depends on sustainable sourcing and processing.

Technology advantages for net zero and Just Transition

Biomass plays a key role in the energy transition, offering both co-firing potential with fossil fuels and full bioenergy plants. Coal and gas plants can be retrofitted to burn biomass, reducing emissions while maintaining grid flexibility. Bioenergy can also provide baseload power, complementing intermittent renewables like solar and wind. The integration of carbon capture technologies (BECCS) could further enhance bioenergy's role in achieving negative emissions, though costs remain a challenge.

Bioenergy supports job creation in agriculture, forestry and power generation, particularly in rural areas. However, large-scale biomass production can lead to deforestation, land-use conflicts and food security concerns. Ensuring sustainable sourcing, local community involvement and ethical supply chains is critical. Governments must regulate bioenergy expansion to prevent negative environmental and social impacts while leveraging its potential for economic development and energy security.

Technology costs

Unlike solar, wind and hydro, biomass has ongoing feedstock costs, comprising 20–50% of total energy costs. LCOE varies widely based on feedstock availability and processing complexity. Residue-based bioenergy can be cost-effective, whereas wood-derived biomass tends to be more expensive. Transportation costs add further variability, emphasising the need for localised sourcing. High capital costs for retrofitting coal plants or integrating BECCS remain barriers to scaling bioenergy.

Technology considerations and vulnerabilities

The sustainability of biomass depends on responsible land use and supply chain management. If biomass is sourced from deforested areas or transported long distances, its carbon footprint increases. Methane emissions from biomass decomposition and combustion require mitigation strategies, such as improved feedstock processing and BECCS adoption. Climate change could also impact biomass availability, as extreme weather affects crop yields. Balancing bioenergy expansion with environmental protection and food security is essential for ensuring its long-term viability.

Geothermal

Technology description

Geothermal energy harnesses heat from beneath the Earth's crust to produce electricity or direct heating. High-temperature reservoirs, often near tectonic activity, provide steam to rotate turbines. In conventional plants, underground water is heated to 150–180°C, generating steam that drives a turbine and powers a generator. Binary steam plants enable lower-temperature geothermal use by transferring heat to a secondary fluid with a lower boiling point. Enhanced geothermal systems (EGS) expand potential by injecting water into hot rock layers to improve permeability, increasing geothermal feasibility beyond volcanic regions.

Technology advantages for net zero and Just Transition

Geothermal provides stable, 24/7 electricity, making it ideal for baseload power and complementing variable renewables like solar and wind. It can also support lithium extraction from geothermal brines, offering a sustainable method for obtaining this critical battery material. Additionally, geothermal can integrate with hydrogen production and carbon storage, enhancing its role in decarbonisation. Advanced technologies, including EGS, could drastically expand geothermal's reach while lowering costs through improved drilling techniques.

From a Just Transition perspective, geothermal supports job creation, particularly for oil and gas workers transitioning to clean energy. Its expansion can drive industrial development and economic diversification. However, risks such as induced seismic activity from fracking must be carefully managed. Governments should implement strong regulatory safeguards, conduct comprehensive geological assessments and ensure community engagement to maximise benefits while minimising disruptions.

Technology costs

Geothermal has a levelised cost of electricity (LCOE) comparable to offshore wind and bioenergy at USD 0.071/kWh, though project costs vary widely due to complex resource exploration. Drilling expenses and site-specific geological challenges make cost prediction difficult. Operational complexities include well depletion, requiring ongoing management and reinvestment. However, new technologies like EGS and closed-loop systems could significantly reduce costs and improve project viability in a broader range of locations.

Technology considerations and vulnerabilities

Geothermal's environmental impact is minimal compared to fossil fuels, but emissions can arise from volcanic activity in geothermal regions. Fracking-based geothermal carries seismic risks, requiring strict monitoring. Additionally, traditional geothermal lacks flexibility, as steam flow cannot be easily controlled. New closed-loop systems allow for greater operational flexibility, but at a higher cost. As geothermal expands, balancing cost, environmental impact and seismic risk will be crucial for sustainable deployment.

Marine

Technology description

Marine energy harnesses the movement of ocean water to generate electricity. The main types include tidal energy, which captures energy from the rise and fall of tides, and wave energy, which converts the kinetic motion of waves into power. Tidal energy is highly predictable but geographically constrained, while wave energy has far greater global potential but remains in the prototype stage. Despite its promise, global marine energy deployment is minimal, with only 527 MW installed. However, technological advances, particularly in wave energy, could accelerate progress in the coming years.

Technology advantages for net zero and Just Transition

Marine energy is a clean, carbon-free power source that complements other renewables. Tidal energy is highly predictable, making it valuable for grid stability, while wave energy can pair well with offshore wind to reduce variability. Co-locating offshore wind and wave farms can optimise costs by sharing infrastructure and transport logistics. Research suggests such hybrid systems could improve reliability, as wind peaks in summer whereas waves intensify in winter.

From a Just Transition perspective, marine energy could support coastal and island economies by reducing reliance on costly imported fuels. It has strong job creation potential in coastal engineering, manufacturing and maintenance, particularly for workers transitioning from fossil fuel industries. However, concerns include potential disruption to fisheries and marine ecosystems. Early engagement with affected communities, comprehensive environmental impact assessments and fair compensation mechanisms will be essential to ensuring equitable development.

Technology costs

Marine energy remains costly compared to other renewables, with tidal energy LCOE at USD 0.20–0.45/kWh and wave energy at USD 0.30–0.55/kWh. However, costs are expected to decline as deployment increases. Some tidal energy projects have already achieved a 40% LCOE reduction in recent years. Further research, economies of scale and improved supply chains could accelerate cost competitiveness, following trends observed in wind and solar energy.

Technology considerations and vulnerabilities

Marine energy faces engineering challenges due to extreme ocean conditions, including storms, saltwater corrosion and biofouling from marine life. High maintenance costs and complex offshore operations make reliability a concern. Environmental impacts, such as turbine-related harm to marine species and potential disruption of ecosystems, require further study. Additionally, with few standardised designs, marine energy supply chains remain underdeveloped, slowing commercialisation. Overcoming these challenges will require targeted investment, regulatory support and continued innovation.

Pumped Hydro

Technology description

Pumped hydro storage (PHS) connects two reservoirs at different elevations to store and release electricity.

During periods of high demand, water is released from the upper reservoir, spinning a turbine to generate electricity. When excess electricity is available, it powers pumps to move water back to the upper reservoir for future use. PHS is the most cost-effective, large-scale energy storage solution and plays a key role in balancing grid demand and integrating variable renewables like solar and wind.

Technology advantages for net zero and Just Transition

PHS provides long-duration energy storage, helping to mitigate renewable energy intermittency. Floating solar PV can be integrated into reservoirs, reducing evaporation and improving solar panel efficiency. Advanced variable-speed turbines further enhance PHS flexibility by allowing rapid response to grid fluctuations. In 2023, the cost of stored water in PHS averaged USD 148/kWh, making it the most affordable large-scale storage option.

From a Just Transition perspective, PHS supports grid modernisation, energy security and job creation. Retrofitting existing hydropower plants with PHS capabilities extends their lifespan while creating employment in construction, maintenance and digital infrastructure. In water-scarce regions, PHS provides co-benefits such as freshwater storage for irrigation. However, deployment must consider environmental impacts and local communities to ensure equitable development.

Technology costs

PHS remains a capital-intensive technology, with installation costs ranging from USD 370–600/kW due to significant infrastructure requirements. Long project timelines for environmental permitting and site selection further slow deployment compared to faster storage alternatives like batteries. Despite these challenges, cost reductions in digitalisation, remote monitoring and predictive maintenance have improved efficiency, making PHS a competitive option for large-scale grid storage.

Technology considerations and vulnerabilities

PHS is highly resilient but faces challenges from climate change, including droughts that affect water availability. Closed-loop systems mitigate these risks by operating independently of river flows, making them viable in water-scarce regions. Digital monitoring enhances reliability by predicting maintenance needs and optimising performance. However, geographical constraints, regulatory barrier, and competition from emerging storage technologies like hydrogen and batteries could impact future deployment.

Battery Storage

Technology description

Battery storage is a rapidly growing solution for electricity storage, with utility-scale systems ranging from a few MWh to hundreds of MWh. Over the last decade, 65% of new battery capacity has been deployed for power generation, with lithium-ion batteries emerging as the dominant technology due to falling costs. Alternative chemistries such as lithium iron phosphate (LFP) and sodium-ion batteries are gaining traction, offering advantages in cost, lifespan and critical mineral dependence.

Technology advantages for net zero and Just Transition

Batteries provide fast-response energy storage, enabling grid flexibility, frequency regulation and black start capabilities. Unlike pumped hydro, batteries are geographically flexible and can be deployed at different scales, including in mini-grids and off-grid areas, supporting universal electricity access. Multi-hour storage technologies, such as redox flow and iron-air batteries, are expanding battery applications beyond short-term grid balancing.

From a Just Transition perspective, battery storage creates jobs in manufacturing, installation and digital optimisation, particularly in urban and remote areas. However, ethical supply chain issues, including human rights violations in lithium and cobalt mining, pose challenges. Governments must implement responsible sourcing policies and support battery recycling initiatives to reduce reliance on raw material extraction and ensure fair labour practices.

Technology costs

Battery costs have dropped by 89% since 2010, from USD 2,511/kWh to USD 273/kWh in 2023, driven by economies of scale and increased global production. LFP batteries now dominate stationary storage due to their lower costs, higher durability and safety advantages.

Continued price declines are expected, with installed capacity utility-scale batteries projected to grow from 54 GW in 2023 to 585 GW by 2030 (IEA, 2024b), making battery storage increasingly cost-competitive.

Technology considerations and vulnerabilities

Batteries enhance grid resilience but face challenges such as raw material supply risks, high temperatures affecting performance and fire hazards. Advances in thermal stability and battery chemistries are improving durability. Regulatory frameworks must evolve to accommodate batteries' dual role as energy consumers and suppliers. While costs are decreasing, upfront investment remains a barrier, requiring policy support and financial incentives to scale deployment.

Thermal Storage

Technology description

Thermal energy storage (TES) stores heat for later electricity generation or direct heating applications. The most common form is concentrated solar power (CSP), which uses mirrors to focus sunlight onto a molten salt-filled tower, later used to generate steam and drive a turbine. While CSP initially competed with solar PV, it is now valued as a thermal storage solution in sun-rich regions. Other TES technologies include enhanced geothermal systems (EGS), which store heated water underground, and solid-state storage, where excess renewable electricity is stored in concrete or rock.

Technology advantages for net zero and Just Transition

TES can stabilise variable renewable energy, storing surplus electricity for later use while offering longer lifespans and lower degradation rates than batteries. It is well suited for sector integration, linking power generation with heating needs. TES can also provide seasonal storage, balancing heat supply between summer and winter, helping to decouple heating demand from electricity grids.

From a Just Transition perspective, TES supports job creation in energy storage, geothermal expansion and infrastructure retrofitting. Its role in decentralised heating solutions enhances energy security in colder climates. However, policy support and investment are needed to scale deployment and ensure equitable benefits across industries and communities.

Technology costs

CSP has reduced its LCOE by 70% since 2010, from USD 0.393/kWh to 0.117/kWh, though deployment has been limited. Installed costs fell by 37%, while capacity factors increased from 30% to 55% in the same period. These improvements enhance TES competitiveness, but uncertain energy system developments make it difficult to forecast future cost trends.

Technology considerations and barriers

TES adoption is hindered by low awareness, limited policy recognition, and competition from battery storage and green hydrogen. Many TES technologies remain in early development, requiring further research and demonstration projects. Additionally, TES integration depends on energy system design, creating uncertainty in investment strategies. Addressing these challenges through policy incentives, R&D funding and long-term energy planning will be key to scaling TES solutions.

Green Hydrogen

Technology description

Green hydrogen is produced through electrolysis, a process that splits water into hydrogen and oxygen using electricity from renewable sources. Unlike fossil fuel-based hydrogen production, green hydrogen emits no direct carbon emissions, making it a crucial tool for decarbonising hard-to-abate sectors. Electrolysis technologies include alkaline, proton exchange membrane (PEM), anion exchange membrane (AEM) and solid oxide, each with varying efficiencies, costs and material requirements. While hydrogen serves as a versatile energy carrier, storage and transport challenges remain due to its low volumetric energy density and potential leakage risks.

Technology advantages for net zero and Just Transition

Green hydrogen plays a crucial role in the transition to net zero emissions by enabling long-term energy storage, integrating renewables and decarbonising industrial processes such as steel, cement and chemicals. Unlike batteries, which are best suited for short-term storage, hydrogen can store excess renewable energy for weeks or months, balancing seasonal demand fluctuations. Additionally, its use in heavy industry, shipping and aviation fills gaps where direct electrification is challenging.

From a Just Transition perspective, green hydrogen offers significant job creation potential, with estimates of up to 6.5 million jobs globally by 2050. Developing economies with abundant renewable resources stand to benefit from hydrogen production and export. However, challenges such as competition for local water and energy resources, potential socioeconomic inequalities and the need for workforce reskilling must be addressed through strong policies and equitable resource allocation.

Technology costs

Green hydrogen remains costly, with production prices ranging from USD 4.5 to 12/kg in 2023, significantly higher than fossil-based hydrogen. Electrolyser technologies such as PEM and alkaline remain expensive due to material and infrastructure costs. Further cost reductions will depend on economies of scale, improved electrolyser efficiencies, and increased investment in infrastructure. Additionally, hydrogen conversion, storage and transport add substantial costs, making long-distance trade economically challenging. Government incentives, subsidies and financial instruments will be key to scaling green hydrogen markets.

Technology considerations and vulnerabilities

Despite its potential, green hydrogen faces several deployment barriers, including technological immaturity, energy losses and safety concerns (Hren et al., 2023). Electrolysis efficiency remains at approximately 66%, requiring significant electricity inputs. Hydrogen storage presents challenges due to its low energy density and need for specialised infrastructure. Safety concerns include high flammability and handling complexities, necessitating rigorous safety protocols. Additionally, regulatory frameworks remain fragmented, slowing market growth. Addressing these issues through policy support, infrastructure investments and technological advances will be essential to unlocking the full potential of green hydrogen in the energy transition.

Technologies for Energy Transmission and Distribution

The integration of renewable energy technologies into the grid requires innovative approaches to system management, particularly for handling variability in generation. The widespread deployment of solar PV and wind power require rapid adjustments in electricity supply. To achieve net zero emissions by 2040 and meet the goal of 88% renewable energy in global electricity generation by 2050, modernising the grid is essential. This includes implementing advanced technologies that enhance flexibility, efficiency and resilience across transmission and distribution systems.

Transmission

Several key technologies improve the efficiency and capacity of electricity transmission networks. Dynamic line ratings (DLR) optimise grid capacity by adjusting transmission line ampacity in real time based on weather conditions, increasing efficiency by 10–25%. Power flow controllers (PFCs), both Flexible AC Transmission Systems (FACTS) and direct current (DC) flow control, optimise the distribution of electricity across the network, improving stability and efficiency. Topology optimisation uses digital twin simulations and AI-driven analytics to manage grid congestion dynamically, reducing infrastructure costs and improving reliability. While these technologies enhance transmission efficiency, challenges include high costs, data accuracy issues and increased system complexity.

Distribution

At the distribution level, technologies such as Advanced Distribution Management Systems (ADMS) improve grid resilience by detecting faults and rerouting electricity automatically, reducing outages and integrating distributed renewables. Conservation voltage reduction (CVR) and voltage/VAR optimisation (VVO) enhance efficiency by stabilising voltage levels and reducing energy losses. Mini-grids offer localised solutions by operating independently or alongside the main grid, increasing system resilience, especially for critical infrastructure and remote areas. Additionally, innovative materials, such as carbon fibre-reinforced cables and amorphous metal transformers, further reduce losses and enhance system efficiency.

Appendix II: Glossary

Advanced Distribution Management Systems: technologies designed to monitor and control electric distribution networks efficiently and reliably.

Agrivoltaics: simultaneous use of land for both solar photovoltaic power generation and agricultural activities. This integrated approach allows for the cultivation of crops or grazing of livestock beneath solar panels, optimising land use and potentially enhancing agricultural productivity.

Bifacial photovoltaics: solar panels designed to capture sunlight on both their front and rear surfaces, thereby increasing their energy generation potential.

Bioenergy: energy produced from biological materials, collectively referred to as biomass. These materials include energy crops, forestry residues, agricultural residues, post-consumer waste and other organic substances. Bioenergy encompasses various forms, such as solid biomass, liquid biofuels, biogas and biomethane.

Bioenergy with carbon capture and storage: a process that combines bioenergy production with carbon capture and storage technology to achieve negative carbon dioxide (CO_2) emissions.

Biogas: gaseous renewable energy source produced through the anaerobic digestion of biomass. This process involves the bacterial decomposition of organic matter in the absence of oxygen, resulting in a gas mixture primarily composed of methane (CH_4) and carbon dioxide (CO_2).

Biogenic CO_2: carbon dioxide emissions resulting from natural biological processes, such as the combustion, decomposition or fermentation of organic materials like wood, plants and other biomass.

Biomass: organic material derived from plants or animals available on a renewable basis. This encompasses a wide range of materials, including energy crops, forestry residues, agricultural residues, post-consumer waste and other organic substances.

Carbon dioxide (CO_2): naturally occurring gas and a by-product of various human activities, notably the combustion of fossil fuels and biomass, as well as land-use changes and certain industrial processes. It plays a pivotal role in the Earth's carbon cycle, moving between the atmosphere, oceans, terrestrial biosphere and lithosphere.

Concentrated photovoltaics: a solar power generation technology that uses lenses or mirrors to focus sunlight onto high-efficiency photovoltaic cells, thereby increasing the electrical output from a given area of solar cells. CPV systems are typically categorised based on their concentration levels.

Concentrated solar power: a system that utilises mirrors or lenses to focus sunlight onto a receiver, heating a fluid to produce steam that drives a turbine for electricity generation.

Conservation voltage reduction: technique employed by electric utilities to reduce energy consumption and peak demand by lowering the voltage supplied to customers within the acceptable range.

Dynamic line rating: a method to optimise the capacity of existing power lines by adjusting their thermal ratings in real-time, based on environmental and weather conditions.

Energy crops: plants cultivated specifically for renewable bioenergy production, rather than for food. These crops can be processed into solid, liquid or gaseous fuels, such as pellets, bioethanol or biogas, which are then used to generate electricity, heat or transportation fuels.

Enhanced geothermal systems: engineered geothermal systems that enable the extraction of Earth's heat for energy production in areas lacking natural hydrothermal resources.

Electrolyser: a device that splits water into hydrogen and oxygen using electricity. When powered by renewable energy sources, this process produces green hydrogen, a clean fuel with applications across various sectors.

Gigawatt: a unit of power equal to one billion watts (10^9 watts) or 1000 megawatts (MW). It is commonly used to express the capacity of large power plants or the total electrical power consumption of sizable regions.

Forestry residues: woody biomass by-products from forestry activities, including branches and leaves, as well as residues from wood processing activities such as sawdust and cutter shavings.

Fossil fuels: hydrocarbons formed from pressurised and heated organic material buried over millions of years. This category includes both primary and secondary (processed) energy products such as coal, peat and peat products, natural gas, oil, oil shale/sands, and other unspecified fossil fuels. These fuels are used for electricity and heat generation, as well as serving as transport fuels.

Power purchase agreement: a long-term contract between an electricity generator and a power purchaser, such as a utility, government entity or company.

Pumped hydro storage: systems that operate by pumping water to an elevated reservoir during periods of low electricity demand and releasing it to generate electricity when demand is high, effectively serving as large-scale energy storage solutions.

Pyrolysis: thermochemical process that decomposes organic materials by heating them to temperatures between 400°C and 600°C in the absence of oxygen.

Renewable energy: energy that can be utilised without diminishing its availability for future generations. This encompasses energy harnessed from natural forces – such as heat, radiation and motion – as well as chemical energy derived from biomass (biofuels).

Reservoir hydroelectric: constructing dams to create reservoirs, allowing for the storage and controlled release of water to generate electricity.

Run-of-river hydroelectric: facilities that generate electricity by utilising the natural flow of rivers without significantly altering their courses or requiring large reservoirs.

Salinity Gradient Energy: a system that harnesses the energy generated from the difference in salt concentration between two fluids, typically where freshwater from rivers meets seawater.

Small-scale hydropower: hydroelectric power installations with a capacity of typically up to 10 megawatts (MW).

Solar PV: direct conversion of sunlight into electricity using electronic devices known as solar cells.

Thin-film amorphous silicon: a type of photovoltaic technology that utilises a non-crystalline form of silicon to convert sunlight into electricity.

Topology optimisation: a technology analysing and optimising the configuration of the electrical grid to enhance efficiency and reliability.

Unabated: processes that proceed without mitigation measures, such as carbon capture or emission reductions.

Utility-scale batteries: large-scale energy storage systems, typically ranging from a few megawatt-hours (MWh) to hundreds of MWh in capacity, designed to provide grid support functions such as frequency regulation and energy shifting.

Variable renewable energy: electricity generation technologies, such as solar photovoltaic and wind power, whose output fluctuates based on the availability of their primary energy sources – sunlight and wind.

Voltage/VAR optimisation: the process of managing voltage levels and reactive power in an electrical distribution system to enhance efficiency, reduce energy losses and maintain power quality.

Appendix III: Additional sources of information on mitigation technologies and practices

1) Solar Photovoltaic

- **Exploiting wind-solar resource complementarity to reduce energy storage need.** Solomon et al. (2020). Link
- **Harvesting the sun twice: Energy, food and water benefits from agrivoltaics in East Africa.** Randle-Boggis et al. (2025). Link
- **IRENA.** *Future of Solar Photovoltaics: Deployment, investment, technology, grid integration and socio-economic aspects.* irena.org
- **The Renewable Energy Institute.** *A Revolution in Solar Power – Perovskite Solar Cells.* renewableinstitute.org
- **Understanding barriers to financing solar and wind energy projects in Asia.** EY. Link
- **US Department of Energy.** *Beyond Recycling: Reducing Waste from Solar Modules Before They're Even Made.* energy.gov

2) Wind Energy

- **Collocating offshore wind and wave generators to reduce power output variability: A Multi-site analysis.** Gideon et al. (2021). Link
- **IRENA.** *Floating Offshore Wind Outlook.* irena.org
- **World Economic Forum.** *The wind power industry is facing major cost headwinds. What's going on (and what can be done)?.* (2023*)* weforum.org
- **World Economic Forum.** *Wind energy projects waiting years for electricity grid connection, and other nature and climate stories you need to read this week.* (2024) weforum.org

3) Hydropower

- **How far are birds, bats, and terrestrial mammals displaced from onshore wind power development? – A systematic review.** Tolvanen et al. (2023). Link
- **International Hydropower Association.** *Hydropower's carbon footprint.* hydropower.org
- **IRENA.** *The Changing Role of Hydropower: Challenges and Opportunities.* irena.org
- **US Department of Energy.** *Reports Show Hydropower's Value Will Likely Grow in Transition to Clean Energy.* energy.gov

4) Biomass

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- **Enhancing climate change resilience in agricultural crops.** Benitez-Alfonso et al. (2023). Link
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- **IRENA.** *Bioenergy for the energy transition: Ensuring sustainability and overcoming barriers.* irena.org
- **US Energy Information Administration.** *Biomass – renewable energy from plants and animals.* eia.gov

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- **National Renewable Energy Laboratory (NREL)**. Enhanced Geothermal Shot Analysis for the Geothermal Technologies Office. nrel.gov
- **Subsidence: an Update on New Zealand Geothermal Deformation Observations and Mechanisms**. Bromley et al. (2015). Link

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- **Biofouling on mooring lines and power cables used in wave energy converter systems – Analysis of fatigue life and energy performance.** Yang et al. (2017). Link
- **European Commission.** *SETIS Magazine: Ocean energy.* **Link.**
- **Harnessing the Power of Ocean Energy: A Comprehensive Review of Power Generation Technologies and Future Perspectives.** Thennakoon et al. (2023). **Link**

- **IEA Ocean Energy Systems.** *Ocean Energy and Net Zero: An International Roadmap to Develop 300GW of Ocean Energy by 2050.* ocean-energy-systems.org
- **IRENA.** *Innovation Outlook: Ocean Energy Technologies.* irena.org
- **Life Cycle Assessment of Ocean Energy Technologies: A Systematic Review.** Paredes et al. (2019). Link

7) Pumped Hydro

- **IRENA.** *Innovative Operation of Pumped Hydropower Storage: Innovation Landscape Brief.* irena.org

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- **IEA.** *Global installed energ ystorage capacity by scenario, 2023 and 2030.* iea.org
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9) Thermal, Geothermal Storage

- **IRENA.** *Innovation Outlook: Thermal Energy Storage.* irena.org

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- **IRENA.** Green Hydrogen Strategy. irena.org
- **IRENA.** Green Hydrogen Cost Reduction. irena.org
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- **The prospects of hydrogen in achieving net zero emissions by 2050: A critical review.** Nnabuife et al. (2023). Link
- **TNO.** Evaluation of the levelised cost of hydrogen based on proposed electrolyser projects in the Netherlands. tno.nl

11) Energy Transmission and Distribution Technologies

- **Applied Energy Services (AES).** Smarter Use of the Dynamic Grid. aes.com
- **Center for Energy and Environmental Policy Research (MIT CEEPR).** A Roadmap for Advanced Transmission Technology Adoption. ceepr.mit.edu
- **Conservation Voltage Reduction in Distribution Networks: A Comprehensive Review.** Alzubi et al. (2025). Link
- **Conservation Voltage Reduction – On the Other Side of the Meter: An Evaluation Case Study.** Stern et al. (2015). Link
- **Grid-enhancing technologies for clean energy systems.** Su et al. (2025). Link
- **IRENA.** Dynamic Line Rating: Innovation Landscape Brief. irena.org
- **Standardizing Conservation Voltage Reduction Measurement & Verification.** Khodaei et al. (2020). Link
- **Transmission Topology Optimisation. Ruiz (2017).** Link
- **US Department of Energy.** Advanced Transmission Technologies. energy.gov
- **US Department of Energy.** Next-Generation Grid Technologies. energy.gov

Appendix IV: Further reading

Climate Technologies in an urban context. https://tech-action.unepccc.org/wp-content/uploads/sites/2/2021/10/2021-06-tna-cities-guidebook-web.pdf

Indigenous Peoples and Climate Technologies. https://tech-action.unepccc.org/wp-content/uploads/sites/2/2021/09/2021-06-tna-indigenous-people-web.pdf

Technologies for Climate Change Mitigation: Agriculture Sector. https://tech-action.unepccc.org/wp-content/uploads/sites/2/2019/04/tna-technologies-for-climate-change-mitigation-agriculture-for-upload.pdf

Technologies for Climate Change Mitigation: Building Sector. https://tech-action.unepccc.org/wp-content/uploads/sites/2/2019/04/tnahandbook-mitigation-building-sector.pdf

Technologies for Climate Change Mitigation: Transport Sector. https://tech-action.unepccc.org/wp-content/uploads/sites/2/2019/04/tnahandbook-transport.pdf

Technologies for Climate Change Adaptation: Agriculture Sector. https://tech-action.unepccc.org/wp-content/uploads/sites/2/2019/05/tna-guidebook-adaptationagriculture.pdf

Technologies for Climate Change Adaptation: Coastal Erosion and Flooding. https://tech-action.unepccc.org/wp-content/uploads/sites/2/2019/04/tnahandbook-coastalerosionflooding.pdf

TECHNOLOGY
NEEDS
ASSESSMENT

This guidebook is part of a series of Technology Needs Assessment (TNA) publications designed to support country teams and practitioners in identifying and prioritizing climate technologies for adaptation and mitigation, with a focus on specific sectors. It provides practical guidance for identifying, assessing, and implementing renewable energy technologies in a country-driven, context-sensitive, and gender-responsive manner, incorporating just transition considerations.

The guidebook offers an overview of up-to-date information on a wide range of relevant renewable energy technologies that can be considered in the development of countries' TNAs - either individually or in combination - depending on specific national circumstances and aligned with development and climate priorities. It is primarily intended for national TNA teams, which include national sectoral experts and stakeholders from government, non-governmental organisations, the private sector, and other relevant groups. However, it may also be useful to other practitioners working in the field.

The development of this guidebook was led by the Technology Executive Committee (TEC), in partnership with UNIDO and UNEP-CCC.