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Technologies for Climate Change Mitigation: Energy

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Guidebook scope and importance

Purpose: Supports technology practitioners and national TNA teams in selecting suitable technologies for **energy generation, storage, and distribution**.

- existing energy technologies available to countries
- provides deployment parameters
- provides just transition considerations
- shares data on costs and open-source resources.

Scope: Covers **energy supply**, **storage**, and **transmission / distribution**. The guidebook excludes demand-side and sector-specific technologies (such as agriculture, buildings, transport)

- Solar PV, wind (onshore and offshore), hydro, biomass, geothermal, marine
- Storage options (batteries, pumped hydro, thermal, green hydrogen)
- Transmission and distribution technologies)

Structure of the guidebook

Chapter 2: overview of interaction between energy and climate

Chapter 3: Analysis of energy technology type

- Technology description
- Advantages and disadvantages
- Economic assessment and affordability
- Mitigation and net zero potential
- Aspects of Just Transition
- Resilience to climate change
- Barriers to dissemination and deployment
- Real-world examples

Chapter 4: Conclusions

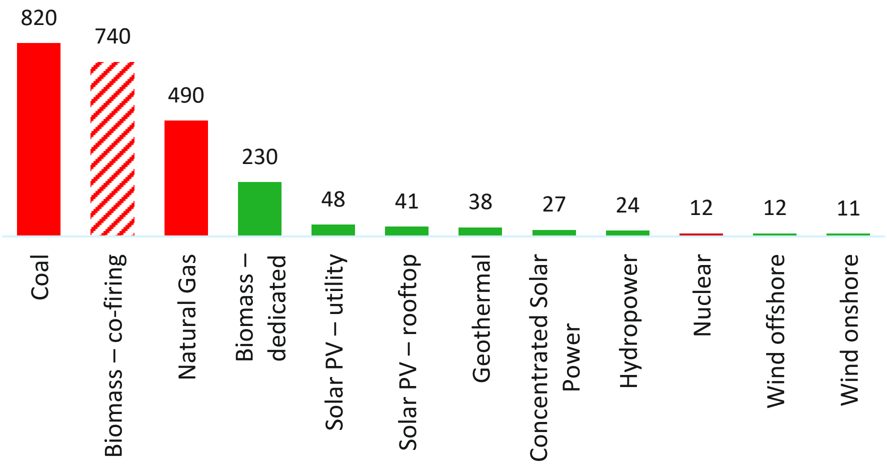
Appendices: Technology Summary Sheets, Glossary, Additional Sources of Information on Mitigation Technologies and Practices, Further Reading

Climate Change and Energy: Achieving Net-zero

Net-zero potential

- The energy sector is the largest contributor to global GHG emissions, with 60% of electricity still generated from coal and natural gas (UNEP, 2024).
- To remain on track for net-zero emissions by 2050 the IEA estimates fossil-based electricity must drop to 30% by 2030.
- Renewables, and especially solar and wind are key to mitigation: 50% of Parties referenced solar energy and 36% referenced wind in their NDCs (UNFCCC, 2023).

Median life cycle emissions per source of electricity generation (gCO2eq/kWh)



Source: IPCC, 2014

Climate Change and Energy: Just Transition, and Gaps/Opportunities

Just Transition

- The IPCC's Sixth Assessment Report (2022) outlines just transition principles, including fair access to energy, creation of decent jobs, gender-specific policies, and intergenerational justice.
- Renewable energy projects can compete with agriculture or impact culturally significant land, especially for indigenous communities. At the same time, they can deliver major benefits—such as energy access and job creation—when inclusive decision-making is practiced.

Gaps and Opportunities

- Solar PV and wind, key to decarbonization, are variable by nature and require integration with baseload renewables like hydropower, biomass, and geothermal. Changing temperatures and weather patterns require a more calibrated mix of renewable generation technologies, as well as more resilient grid systems.
- Key solutions include: utility-scale storage, decentralized systems, grid innovation, and smart demand-side management, and continued tech progress

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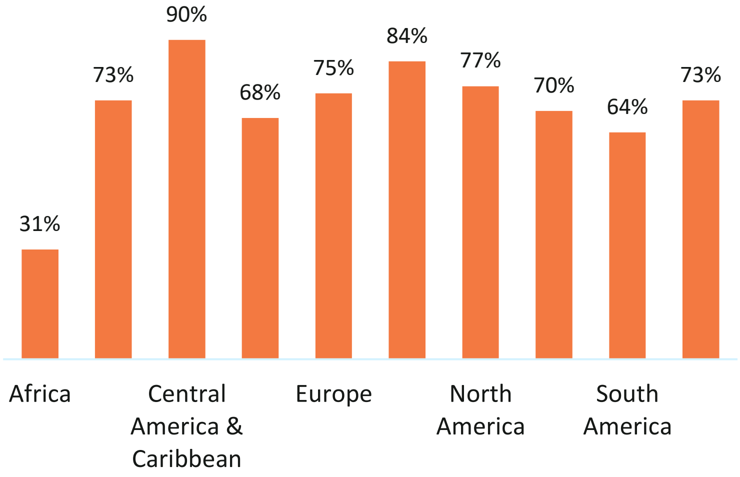
Solar PV

- Solar PV converts sunlight into electricity using semiconducting silicon layers. With various panel types (mono-, polycrystalline, thin-film), global **solar PV capacity must more than double** to 6,000 GW by 2030 to stay on track for net-zero goals.
- From 2010 to 2023, utility-scale solar **PV LCOE fell by 90%,** driving USD 20 billion in avoided fuel costs in 2023 alone. However, **costs vary widely** – installation in South Africa can be twice as expensive as in Spain due to financing and regulatory barriers.
- Solar PV projects can generate **substantial local employment**, particularly in installation and maintenance, and women already make up **40% of the workforce**. However, they require **large land areas** and water for panel cleaning, raising concerns over land access, biodiversity, and community impacts.
- Solar PV deployment is **hindered by capital costs**, **grid integration issues**, and **manufacturing concentration**. Solutions include **agrivoltaics**, **dry-cleaning systems**, **local panel production**, and **financing innovations** like green bonds and credit guarantees.

Solar PV share of new RE capacity additions



Source: IRENA, 2023

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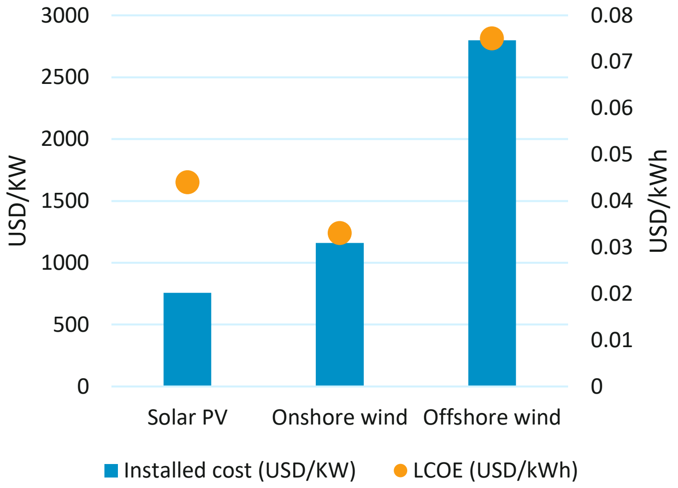
Wind

- Wind energy converts wind into electricity through turbines, with onshore and offshore systems now reaching weighted capacity factors of 36% and 45% respectively. **Offshore wind offers higher output** and **nighttime generation**, complementing solar PV and enhancing grid reliability.
- Between 2010 and 2023, **the LCOE of onshore wind dropped 70%, and offshore by 63%**, with **onshore now the lowest-cost** mature renewable source. However, offshore systems remain capital-intensive due to **harsh marine conditions**, **specialized infrastructure**, and corrosion risks.
- Wind projects can disrupt rural or indigenous lands, requiring careful siting and inclusive planning. They offer **quality job opportunities** across installation, **maintenance**, **shipbuilding, and logistics**, especially in offshore wind, supporting economic diversification.
- Wind faces challenges from **permitting delays**, **rising material costs**, and **high WACC in developing economies**. Solutions include streamlined permitting, offshore energy hubs, and pairing offshore wind with green hydrogen production.

Installed costs and LCOE for onshore, offshore wind & solar PV

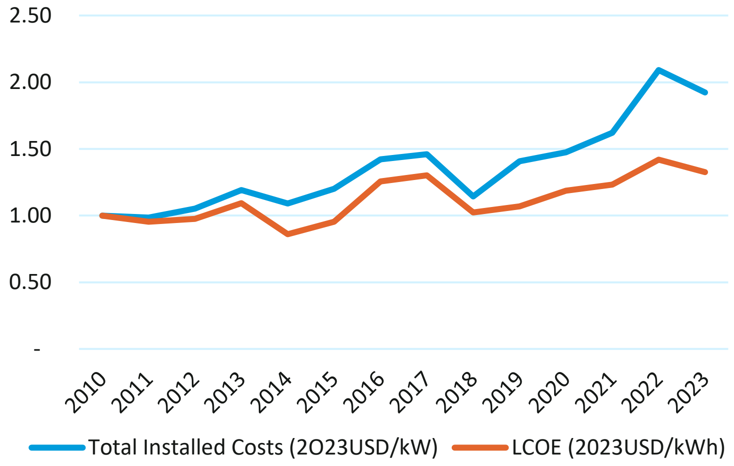


Source: IRENA, 2023

Hydropower

- Hydropower **generates electricity from flowing water** using dams or run-of-river systems and plays a crucial role in grid balancing and frequency regulation. **Pumped storage** acts as a highly efficient storage solution, especially when paired with solar or wind.
- Unlike other renewables, **hydropower costs have risen**—LCOE up 33% and installed costs up 92% between 2010 and 2023—due to complex site-specific construction and **long lead times**. Small hydro can be more cost-effective and locally sourced but still faces terrain challenges.
- Hydropower offers socioeconomic benefits like **irrigation**, **flood control**, and **job creation**, especially with small-scale projects. However, large-scale dams can **displace communities**, impact indigenous land rights, and alter ecosystems.
- Key barriers include **high upfront costs**, long permitting processes, and **site-specific customization**. Climate resilience measures—like raising dam heights, early warning systems, and hybridization with solar—are essential to address drought risks and ensure long-term viability.

Indexed installed costs and LCOE for hydropower (2010-2023)

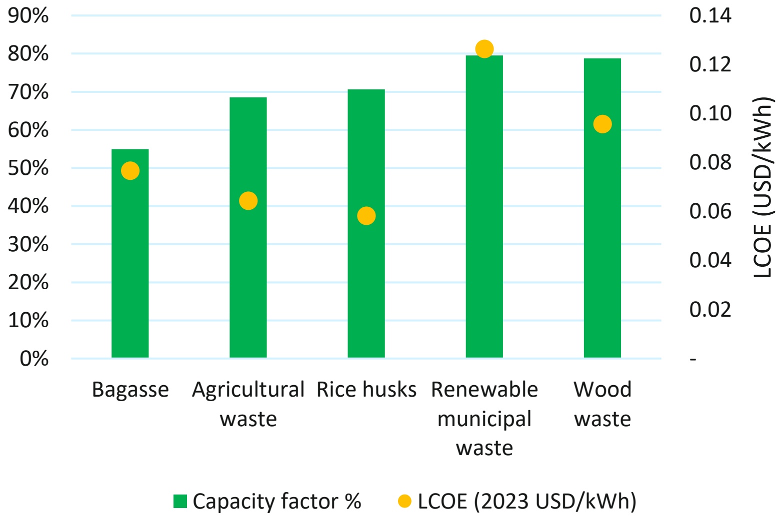


Source: IRENA, 2023

Biomass

- Biomass converts organic materials into electricity via combustion or thermochemical conversion, with potential for negative emissions when paired with BECCS. It offers **baseload power** and grid flexibility, but only approaches carbon neutrality when **sustainably and locally sourced**.
- Feedstock **accounts for 20–50%** of biomass power generation costs, with **large variability** depending on material type and transport distance. While some projects using local residues achieve very low LCOE, others face high costs.
- Biomass can create **rural jobs** and provide **extra revenue for farmers and waste collectors**, especially when focused on agricultural or municipal waste. However, risks include **air pollution**, **land use conflicts**, **deforestation**, and pesticide runoff, requiring careful planning and safeguards.
- Deployment is limited by **feedstock availability**, high transport and retrofitting costs, and financing hurdles. Climate resilience depends on **crop diversification**, **drought-resistant species**, and **sustainable land-use strategies** to protect feedstock supply in a changing climate.

Capacity factor and LCOE for different types of biomass feedstocks

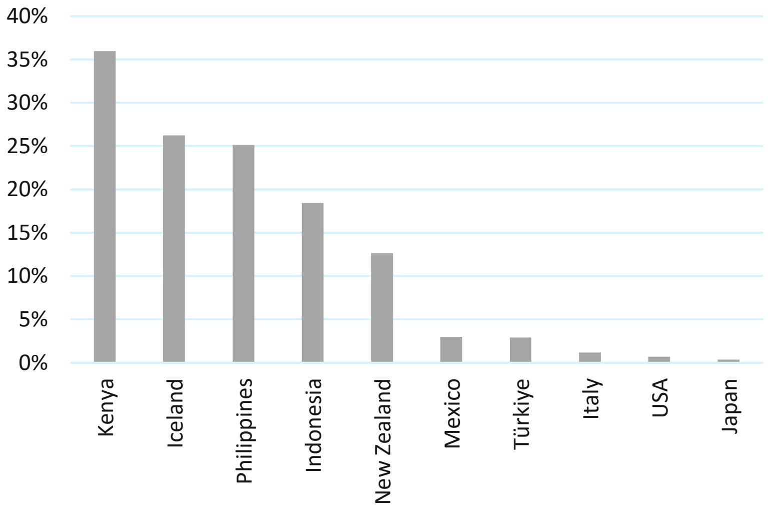


Source: IRENA, 2023

Geothermal

- Geothermal harnesses **underground heat** to generate continuous, baseload electricity, using steam or binary cycle systems. It emits ~38 gCO_2eq/kWh—**low compared to fossil fuels**—and has potential for **mineral co-extraction** (e.g., lithium) and green hydrogen production.
- With an average LCOE of USD 0.071/kWh, geothermal is **cost-competitive with offshore wind and bioenergy**. However, high **upfront exploration costs**, **drilling risks**, and **complex operations** contribute to financial uncertainty and slow deployment.
- Projects can **boost local employment and infrastructure** but must address water use, land acquisition, and pollution risks (gas emissions, seismic activity). Fair compensation, health monitoring, and environmental safeguards are essential.
- Challenges include **high drilling costs**, **limited high-temperature sites**, and **financing gaps**. Enhanced and closed-loop systems offer promise, while improved geological mapping and permitting reform can accelerate safe, resilient deployment.

Geothermal share over total RE installed capacity



Source: IRENA, 2023

Marine

- Marine energy includes tidal and wave technologies that harness ocean movement to generate clean power, with near-zero operational emissions. Despite **vast global potential** (e.g. 29,500 TWh for wave), **installed capacity remains negligible** at 527 MW.
- **LCOEs remain high** (USD 0.20–0.45/kWh for tidal; USD 0.30–0.55/kWh for wave), with **limited commercial deployment** and high capital costs. **Promising cost declines** mirror early wind/solar trends, especially with co-location of offshore resources.
- Marine projects can create **10+ jobs/MW** and build local resilience, **especially in SIDS**. Prioritizing local hiring, training, and port-based manufacturing can strengthen regional economies, while minimizing ecosystem disruption is key to equitable deployment.
- Engineering challenges include **corrosion**, **biofouling**, and **storm damage**, while financial and **supply chain gaps limit scalability**. Pilot projects in Ghana and Japan show viability, but broader adoption needs R&D, standards, and supportive policy.

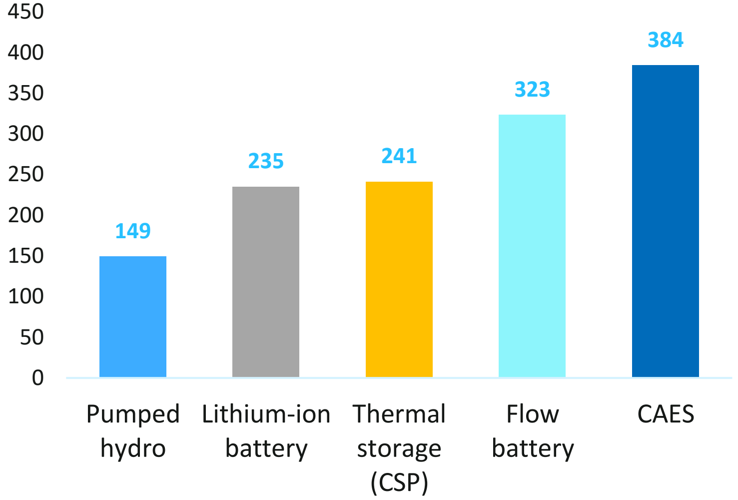
Ada Foah Marine Energy Project in Ghana

Source: IRENA, 2023

Storage

- **Battery storage** has rapidly scaled, led by lithium-ion technologies, offering fast frequency regulation, black start capabilities, and decentralized energy access. **Cost reductions of 89%** (2010–2023) and **flexible deployment** make batteries key for peak shaving, renewable integration, and mini-grid support.
- **Thermal** and **geothermal storage** provide **longer lifespans** and **sector integration advantages**, such as using excess heat for buildings or industrial processes. Technologies like **CSP** and **enhanced geothermal** offer seasonal storage and backup for variable renewables, especially in sunny, arid regions.
- **Green hydrogen** enables **long-duration energy storage** using electrolysis powered by renewables, suitable for seasonal balancing and hard-to-abate sectors.

Compared storage technology costs, 2023



Source: IRENA, 2023

Transmission and Distribution

- The **integration of variable renewables** like solar and wind demands a **flexible**, **responsive**, and **robust** grid system. Enhancing grid adaptability is crucial for maintaining system reliability.
- Innovations like **Dynamic Line Ratings (DLR)**, **Power Flow Controllers (PFC)**, and **Topology Optimization** increase capacity, reduce congestion, and maximize existing infrastructure use. **ADMS**, **CVR**, and **VVO** systems improve distribution reliability, reduce energy waste, and lower costs.
- **Mini-grids** improve energy access in remote areas, support critical services, and allow communities to generate and manage local clean energy. They are especially vital for **resilience during outages** and disaster recovery.
- These technologies help grids adapt to **climate risks** by **improving outage response**, **reducing thermal stress**, and **reinforcing physical durability**. Undergrounding cables, upgrading materials, and vegetation management strengthen system reliability.
- Barriers include **high costs**, **regulatory hurdles**, and the **need for technical expertise and data integration**. However, successful deployments in the UK, US, Kenya, and India show strong potential for emissions reductions, cost savings, and social benefits.

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Conclusions

Generation technologies

Solar PV and wind may be **prioritized** where viable, **complemented** by hydropower, biomass and geothermal to ensure **dispatchable, reliable power**.

Countries may **tailor their mix** to available resources: solar PV in high-irradiance zones, geothermal in tectonic regions, wind in areas with high wind speed, etc.

Countries may consider the **latest technological innovations** in solar PV, hydro, geothermal, and wind to sustain rising temperatures and more extreme weather patterns

Storage and grid technologies

Smart grid upgrades like ADMS, DLR, PFCs, and topology optimization improve load balancing, outage response and integration of variable renewables. **Grid resilience** against climate events may at the same time be pursued.

Pumped hydro, lithium-ion, sodium-ion, CSP with thermal storage, and green hydrogen **enhance flexibility, reliability and long-term dispatchability**.

Cross-border electricity trade, local manufacturing capacity and distributed infrastructure improve resilience, reduce costs and enhance energy security.

Just transition policies

Retraining programs and **targeted employment** in geothermal, offshore wind or battery sectors create equitable workforce pathways.

Mini-grids, small hydro and community-owned projects **increase energy access** in rural areas while generating local economic opportunities.

Land use conflicts can be avoided through agrivoltaics and participatory planning as well as increasing energy crop yield and efficiency; projects must uphold labour rights and gender equity.

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Thank you!