Carbon-Free Electricity in G20 Countries

Status and the way forward

International Energy Agency

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Abstract

In 2024, the Republic of Korea proposed the Carbon-Free Energy (CFE) Initiative to promote the use of technology-neutral, carbon-free energy to decarbonise the energy sector.

In line with this initiative, Korea’s Ministry of Trade, Industry and Energy (MOTIE) commissioned this report to analyse the status and prospects of carbon-free energy in the electricity sector in G20 countries, and to provide policy recommendations to advance its progress.

The International Energy Agency (IEA) and the Korea Energy Economics Institute (KEEi) jointly produced this report.

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Chapter 1. Introduction

Decarbonising our electricity systems and electrifying energy demand currently being met by fossil fuel-based energy can accelerate the transition to clean energy. To advance good practices that promote carbon-free electricity deployment, this study compares carbon-free electricity status, relevant barriers and different policies of G20 countries. Countries are grouped into clusters based on shared characteristics related to carbon-free energy (CFE). The final chapter presents both cluster-specific and cross-cluster policy recommendations. This report was written based on information available as of December 2024.

This introductory chapter, which is intended to serve as a foundation for future analyses, provides a term definition and an overview of current status. The first section contextualises the term "carbon-free" and describes the scope of the energy sources studied, while the second highlights differences in installed capacity and generation mix shares among countries and contains a comprehensive set of policy tables.

What is carbon-free energy?

Through the Carbon-Free Alliance, the Korean government supports joint efforts to advance carbon-free energy systems. However, because the Carbon-Free Alliance uses the notion of technological neutrality, carbon-free energy sources are not explicitly defined. This report includes only carbon-free energy sources that generate electricity without emitting carbon dioxide: solar PV, wind, nuclear, bioenergy[1], ocean, geothermal, hydropower and hydrogen.

Differences among G20 countries

The expansion of carbon-free energy is essential for achieving carbon neutrality. However, as each country faces different circumstances, it is not feasible to recommend a specific power generation source applicable to all. Therefore, policies for expanding carbon-free energy need to be developed in consideration of each country's unique situation. Given their current power generation mixes, the analysed countries have very different starting positions as well as distinct approaches to decarbonise their energy systems. While many country plans focus on renewable energy sources (RES), some leverage nuclear energy and others rely on significant hydropower resources. Choices of installed capacity reflect not

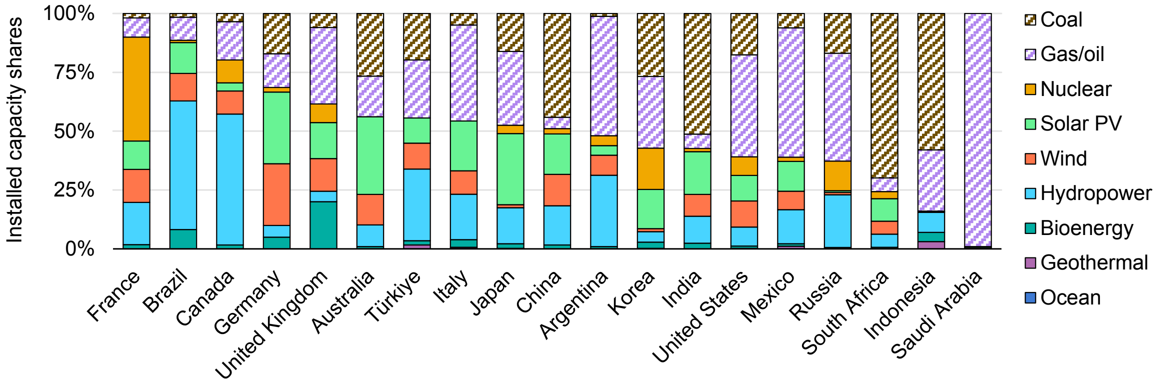
[1] This report covers bioenergy with carbon capture and storage (BECCS).

only policy decisions, but a variety of factors such as a country's natural endowments, level of interconnectedness, and ability to integrate variable renewable energy (VRE).

This section provides an overview of installed capacities; carbon-neutrality and renewable energy targets; notable policies for boosting renewable energy deployment; stances on nuclear energy; and the use of carbon trading schemes.

Comparison of installed capacity

Installed capacity shares in G20 countries, 2022



Notes: Coal and gas/oil are considered non-carbon-free energy sources, whereas ocean, geothermal, bioenergy, hydropower, wind, solar PV and nuclear are considered carbon-free energy sources.

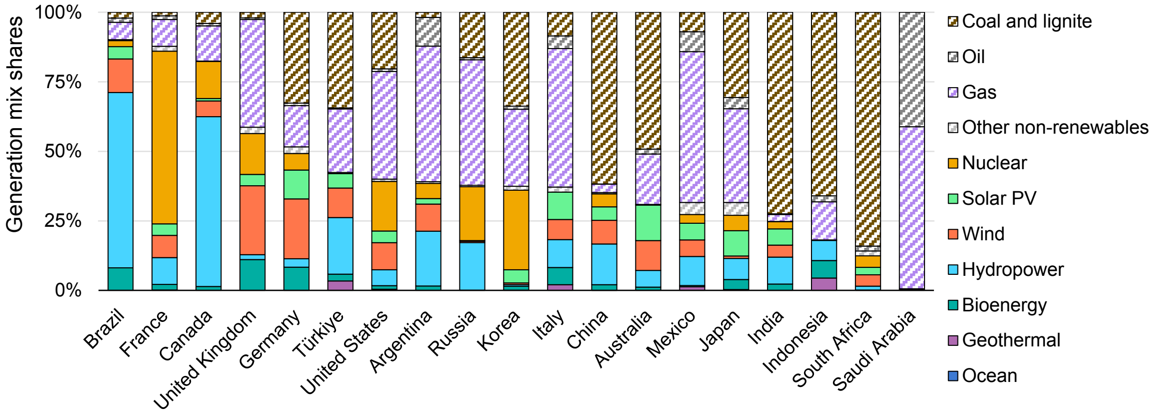
Sources: IEA analysis based on IEA (2024), Renewable Energy Progress Tracker (accessed 26 January 2025), and Global Energy Monitor (2024), Global Integrated Power Tracker (accessed 26 January 2025).

While installed capacity refers to the total electricity output a country's energy sources can produce at full load, electricity generation mix denotes the actual breakdown of electricity produced from different sources over a given period. A specific share of installed carbon-free capacity does not directly translate into an equivalent share in the generation mix. This discrepancy stems from the lower capacity factors of wind and, particularly, solar PV, meaning that installed capacity shares do not align proportionally with generation mix shares.

Furthermore, variable carbon-free energy sources need dispatchable backup or leveraging flexibility in the system. A carbon-free generation mix can therefore include dispatchable energy sources such as nuclear and hydropower to provide firm electricity capacity. While a country may have a significant share of installed RES capacity, its reliance on variable renewables can still lead to a generation mix that includes dispatchable conventional sources to maintain grid stability.

Comparison of electricity generation mix

Electricity generation by source in G20 countries, 2022



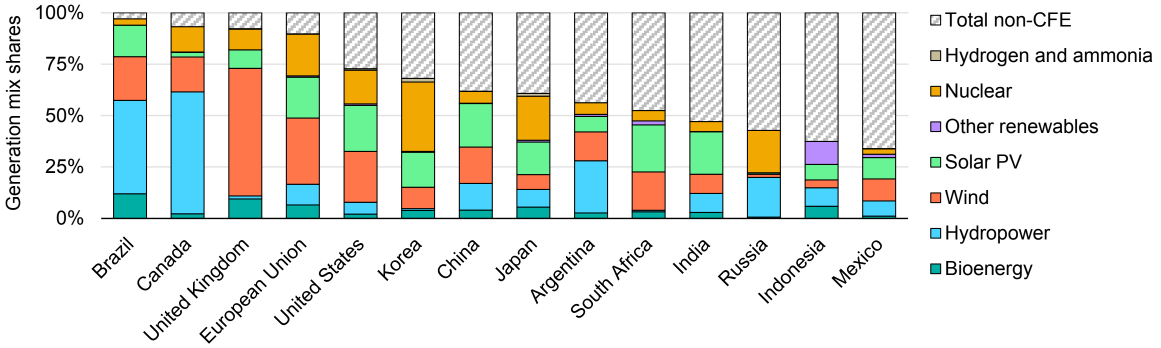
Note: Coal and lignite, oil, gas, and other non-renewables (including pumped hydropower) are considered non-carbon-free energy sources, whereas ocean, geothermal, bioenergy, hydropower, wind, solar PV and nuclear are considered carbon-free energy sources.

Electricity generation by carbon-free energy source in selected G20 countries by 2030

Assuming that governments achieve their announced energy and climate targets in full and on time, the electricity generation mix is expected to be considerably different by 2030 (see the graph below). Under this assumption, solar PV and wind shares in electricity generation are projected to increase sharply, contributing the most CFE generation by 2030, in all selected countries except the Russian Federation (hereafter, "Russia").

In countries where policies favour nuclear energy expansion, both lifetime extensions and new constructions will drive generation growth. Hydropower is also anticipated to contribute to the expansion of carbon-free electricity generation, but its growth will be relatively modest.

Projected electricity generation by source in selected G20 countries, 2030



Notes: CFE = carbon-free energy. Solid colours represent CFE sources and shaded ones stand for non-CFE sources. Values are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario.

Announced carbon-neutrality and renewable electricity targets

Overview of implemented renewable energy sources targets in G20 countries

	Announced net zero target	Renewable energy sources target
Argentina	By 2050	By 2025, non-hydropower RES make up 20% of electricity generation
Australia	By 2050	By 2030, 82% of electricity generation from RES, doubling RES capacity every decade
Brazil	By 2050	By 2030, RES generation makes up 84% of electricity generation
Canada	By 2050	By 2030, 90% of electricity generation from RES
China	By 2060	By 2025, 33% of electricity generation from RES (without hydropower, 18%)
European Union	By 2050	By 2030, 42.5% of electricity sourced from RES (with the aspiration to reach 45%)
France	By 2050	By 2030, installed capacity of 54-60 GW of solar PV; 33-35 GW of onshore wind; and 3.6 GW of offshore wind
Germany	By 2045	By 2030, 80% of electricity generated from RES
India	By 2070	By 2030, 50% of installed power generation capacity in non-fossil fuel-based generation
Indonesia	By 2060	By 2030, 19-21% of electricity sourced from RES
Italy	By 2050	By 2030, 55% of electricity generated from RES
Japan	By 2050	By 2030, 36-38% RES energy target

	Announced net zero target	Renewable energy sources target
Korea	By 2050	By 2030, 20% of electricity produced from RES
Mexico	By 2050	By 2030, 45% of electricity generation from RES
Russia	By 2060	By 2030, to double renewable energy capacity
Saudi Arabia	By 2060	By 2030, 130 GW of renewable power capacity
South Africa	By 2050	By 2030, 41% RES energy
Türkiye	By 2053	By 2030, 50% renewable energy
United Kingdom	By 2050	By 2035, 100% of electricity generation decarbonised
United States	By 2050	By 2035, 100% of electricity generation decarbonised

Overview of implemented policies

The following table outlines the main policies implemented in the past five years to support renewable energy deployment, and the subsequent country profiles further describe each policy. Most countries have introduced renewable energy auctions, financial support mechanisms, or tax credits or loans at favourable interest rates.

Key policies implemented to promote renewable energy uptake in G20 countries

	RES policy/driver
Argentina	• RES auctions: RenMDI and RenovAr • Financial support for individuals and small and medium-sized enterprises (SMEs) • Tax credit certificates: National Programme for Distributed Generation
Australia	• RES auctions: Capacity Investment Scheme • Power purchase agreements (PPAs) • Individual installation support: Powering Australia
Brazil	• RES auctions • Favourable-interest-rate loans from the National Bank for Economic and Social Development • PPAs, net metering
Canada	• RES auctions in some provinces • Financial support for individuals • Federal tax credits

	RES policy/driver
China	• RES auctions: feed-in tariffs - yet their gradual phaseout • PPAs at provincially set benchmark electricity prices • Country PV pilot that mandates solar PV installations
France	• RES auctions • Financial support for individuals and SMEs • Solar PV rooftop obligation for non-commercial buildings
Germany	• RES auctions • Feed-in tariffs and premiums for distributed solar PV • A growing corporate PPA market
India	• Auction-driven capacity additions conducted by distribution companies (DISCOMs) • Support for distributed solar PV • RES hybrid auctions
Indonesia	• Financial support through: Just Energy Transition Partnership • Preferential access to low-carbon electricity for poor households
Italy	• RES auction • VAT and property tax exemptions
Japan	• RES auctions: feed-in premiums, newly introduced for residential and commercial power consumers • RES installations in public buildings: Basic Policy for Green Transformation • Financial support through Green Innovation Fund
Korea	• RES auctions • Renewable portfolio standards • National incentives through certificates and support from municipal governments
Mexico	• RES auctions: capacity and energy auctions • Clean energy certificate auctions • Net metering
Russia	• RES auctions: capacity and energy auctions • Investment incentives • State financial support
Saudi Arabia	• Bilateral contracts with state-owned utility • PPAs • RES auctions: capacity and energy auctions
South Africa	• RES auctions: competitive tenders • RES auctions: feed-in tariffs • Lower licensing thresholds for RES for self-consumption
Türkiye	• RES auctions: YEKA • Feed-in tariff support scheme: YEKDEM • Financial support for public and private climate projects

	RES policy/driver
United Kingdom	• RES auctions: contracts for difference (CfDs) • PPAs • Financial support for individuals, businesses and research projects, e.g. floating offshore installations
United States	• RES auctions, tax incentives • State-level: renewable portfolio standards • Clean energy tax credits and incentives, federal tax incentives

Nuclear energy policy agenda

G20 countries have varying approaches to nuclear energy, whether phasing in new capacity, expanding it or phasing it out. Analysing these differences reveals valuable insights into how nuclear power fits into broader energy strategies, impacting energy security, integration of non-dispatchable renewable energy sources, and the overall transition to sustainable energy systems.

Policy agendas on nuclear energy of selected countries

Considering	Phasing in	Keeping steady	Expanding	Phasing out
Australia, Indonesia, Italy, Saudi Arabia	Türkiye	Japan	Argentina, Brazil, Canada, China, France, India, Korea, Mexico, Russia, South Africa, United Kingdom, United States	Germany

Notes: "Considering" refers to countries initially exploring the development of nuclear capabilities, which may include the drafting of white papers or the signing of memoranda of understanding. "Phasing in" applies to countries that have already begun to construct their first nuclear reactors. "Expanding" denotes countries that have made efforts to increase their installed nuclear power capacity, for instance by passing laws that mention building new reactors.

Sources: IEA analysis based on World Nuclear Association and news reports.

Introduced carbon trading schemes

Some G20 countries have yet to introduce a carbon trading scheme. India and Indonesia recently launched carbon trading initiatives, while Brazil and Türkiye are in the process of implementing one. However, among G20 countries with existing carbon trading schemes, the scope of carbon coverage and the prices of carbon vary significantly.

Overview of carbon trading schemes and their coverage in G20 countries

	Carbon trading scheme introduced	Coverage
Argentina	Yes	Low
Australia	No	None
Brazil	No	None
Canada	Yes	High
China	Yes	Medium
France	Yes	Medium
Germany	Yes	High
India	Yes	Low
Indonesia	Yes	Low
Italy	Yes	Medium
Japan	Yes	High
Korea	Yes	High
Mexico	Yes	Medium
Russia	No	None
Saudi Arabia	No	None
South Africa	Yes	High
Türkiye	No	None
United Kingdom	Yes	Medium
United States	Yes	Low

Notes: Coverage of total GHG emissions: High = >66%; Medium = 33-66%; Low = <33%; None = 0%. Voluntary carbon trading schemes fall into the "No" category.

Source: IEA analysis based on Climate Transparency (2022), Climate Transparency Report 2022, accessed 26 January 2025.

Chapter 2. Comprehensive status and policy overviews

This chapter's in-depth overviews of G20 countries examine their policy frameworks, including announced pledges, historical and current policy developments (i.e. of the past five years), political discourse on nuclear energy, obstacles to deploying low-carbon energy sources, and opportunities for growth.

African Union

Policy analysis

The African Union (AU) has not established a formal carbon neutrality target but has undertaken a range of climate strategies and initiatives to reduce greenhouse gas emissions and support renewable energy capacity adoption. Central to these efforts is the Climate Change and Resilient Development Strategy and Action Plan for 2022-2032, designed to guide Africa's transition to a low-emission future by harnessing the continent's unique emissions-mitigation potential. A key element of this strategy is the Green Recovery Action Plan, which underscores the critical role of renewable energy and energy efficiency measures in driving emissions reductions.

The AU strategy emphasises resilience-building and enhancing adaptive capacity while identifying low-emission development pathways tailored to Africa's specific needs. To support these activities, the African Union is advocating for increased climate financing from international partners. Effective governance and robust policy frameworks – such as anticipatory governance – are recognised as essential for the successful implementation of climate-resilient development strategies.

Additionally, the African Union has introduced initiatives such as the Climate Action Innovation Hub, launched in 2023 to engage youth and women in climate action by fostering projects aligned with its broader strategic objectives. This initiative highlights the AU commitment to inclusive participation and the widespread expansion of climate solutions across Africa.

Meanwhile, the African Commission on Nuclear Energy (AFCONE) actively promotes the use of nuclear technology to drive socioeconomic progress across the continent. AFCONE supports efforts to build nuclear energy capacity in Africa, including through collaborations with international organisations, to enhance nuclear sector skills, expertise and financing. In 2023, AFCONE and the World Nuclear Association signed a memorandum of understanding to facilitate information sharing and support the development of nuclear energy in Africa.

In the area of hydrogen, AU member states could capitalise on their substantial renewable energy potential to produce green hydrogen. Furthermore, the African Union has secured funding from the European Union to develop an African Green Hydrogen Strategy and Action Plan.

While the African Union does not have legislative authority over its member states, it can strongly influence members to adopt policies consistent with AU frameworks, decisions, recommendations and strategies.

Opportunities for growth

The IEA forecasts that AU member states will collectively achieve a 33% share of renewable energy in power generation by 2030. By then, variable renewable energy sources are expected to account for 13% of the electricity generation mix. With further additional installed capacity, hydropower will remain the dominant carbon-free energy source. However, with the shares of other renewable energy sources expanding towards 2030, the hydropower portion of installed renewable energy capacity is projected to decline to 34% in 2030 from 58% in 2023.

The number of utility-scale solar PV installations is anticipated to grow significantly, representing 37% of renewable energy capacity by 2030, while distributed solar PV systems will contribute slightly more than 10%. Onshore wind is expected to hold steady at approximately 13% in 2030. Overall, the total capacity of renewable energy sources, excluding nuclear, is projected to increase roughly 150% from the 2023 level by 2030.

Argentina

Policy analysis

Argentina aims to achieve carbon neutrality by 2050 through a long-term strategy introduced by the government.

In early 2023, Argentina unveiled a new renewable energy auction programme, RenMDI, to supplement the previous auction programme, RenovAr, launched in 2016. RenMDI was designed to promote renewable energy projects at a smaller scale than the RenovAr programme. They both aim to increase the share of renewable energy in Argentina's electricity matrix, but they target different energy market segments and project sizes. RenMDI focuses on smaller-scale renewable energy projects, typically 500 kW to 10 MW in capacity, and it is designed to be implemented in areas where large-scale projects such as those of RenovAr may not be feasible due to transmission capacity limitations or geographical constraints.

Solar PV emerged as the dominant technology in auctions under the RenMDI scheme, driving distributed solar PV expansion in the country, with 500 MW anticipated to come online within the next five years. By law, costs are distributed among all consumers under this renewable auction scheme. Furthermore, in 2023, a financial support scheme under the existing Fund for the Distributed Generation of Renewable Energies framework was launched to help small and medium-sized enterprises (SMEs) and larger companies acquire solar PV systems. Prior to this initiative, Argentina had created the Fund for the Development of Renewable Energies to offer independent power producers significant fiscal incentives, including tax exemptions, accelerated depreciation and VAT refunds. Meanwhile, the National Programme for Distributed Generation uses tax credits to promote renewable energy installations.

In 2023, Argentina introduced a national hydrogen strategy and launched a hydrogen initiative to enhance dialogue between the private and public sectors. The national hydrogen roadmap envisions 5 Mt of hydrogen production annually by 2050, with the majority designated for export.

Differences between RenMDI and RenovAr

Feature	RenMDI	RenovAr
Project size	500 kW to 10 MW (small to intermediate scale)	Generally large-scale projects (>10 MW)
Target market	Local markets, distribution networks, isolated areas	National grid, utility-scale generation
Geographical focus	More localised, rural and off-grid areas	National scope, connected to the main grid
Goal	Support for decentralised generation and local energy	Large-scale renewable energy capacity expansion
Technology scope	Solar, wind, biomass, biogas, small hydro	Similar technologies but large-scale focus
Auction structure	Smaller-scale auctions for specific areas	Larger national-level auctions for massive capacity

Opportunities for growth

Argentina's renewable energy capacity is projected to grow by just over 40% from 2023 to 2030, with solar PV doubling to lead capacity additions.

Although hydropower remains Argentina's largest source of renewable energy, its expansion will proceed at a slower pace than previously expected due to financial and permitting challenges that hinder project development. Notably, the Portezuelo hydropower plant is undergoing additional environmental assessments because of political and social acceptance issues. Construction has not yet begun and, according to the project's work plan, the plant is not expected to become operational before 2030. Furthermore, development of the 1.3-GW La Barrancosa-Cóndor Cliff hydroelectric complex is progressing slowly.

Argentina currently operates three functional nuclear reactors that collectively cover roughly 5% of its electricity generation, but it has been discussing the possibility of developing new nuclear power plants, including floating ones. For instance, it is considering adding a reactor at its Atucha site in collaboration with the People's Republic of China (hereafter, "China"). In addition, the country's first small modular reactor, Carem25, is to be connected in 2027.

Australia

Policy analysis

Australia has pledged to achieve carbon neutrality by 2050. Its plan involves significant investments in low-carbon energy sources, including hydrogen, to double renewable energy generation every decade until 2050. In fact, the Australian government is targeting 82% electricity generation from renewable energy sources by 2030.

In 2022, it launched the new National Energy Transformation Partnership to attract private investments crucial for transmission and renewable energy projects, including expanding the Capacity Investment Scheme (CIS) to achieve 32 GW of new capacity nationwide by 2030. The CIS aims to compensate for the anticipated supply scarcity stemming from the phaseout of ageing coal power stations by expanding renewable energy auctions. Also since 2022, households and small and medium-sized enterprises have been receiving community grants to acquire batteries, ideally reducing their electricity consumption and lowering electricity bills.

Furthermore, through its Renewable Energy Zones (REZs) framework, Australia aims to tap into the energy potential of regions with abundant wind and solar resources. The REZs identified by the Australian Energy Market Operator's Integrated System Plan are areas where large renewable energy projects can be developed. Planning and investing in transmission infrastructure can support these installations by facilitating their integration into the national grid while ensuring system reliability and grid stability.

In 2021, the Comprehensive Strategic Partnership strengthened economic and diplomatic co-operation between Australia and Korea, with the countries signing a memorandum of understanding to enhance supply chain resilience and co-operation. Australia has also intensified international co-operation and investments in renewable energy projects through a Technology Investment Roadmap and has established a framework for offshore wind project development, maintenance and decommissioning. Furthermore, in 2022 Australia and the United States launched the Net Zero Technology Acceleration Partnership, prioritising collaboration in developing long-duration energy storage solutions, digital electricity grids, and technologies that enable the integration of variable renewable energy, hydrogen and CO_2 removal.

So far, the Australian government has not considered the possibilities of nuclear power. Nevertheless, Australia's Nuclear Science and Technology Organisation (ANSTO) closely follows global nuclear energy developments, including small modular reactors.

Thanks to its abundant and affordable solar PV and wind resources as well as its proximity to key Asian markets, Australia is well positioned to become a leading exporter of hydrogen and hydrogen-based fuels. The country is currently developing national hydrogen codes of best practices for hydrogen and ammonia production, refuelling and storage safety. The Australian Clean Hydrogen Trade Partnership, established with AUD 150 million in funding since 2022, supports clean hydrogen investments, particularly exports to Japan under the Japan-Australia Partnership on Decarbonisation Through Technology launched in June 2021.

Additionally, Australia's Regional Hydrogen Hubs initiative, launched in 2022, promotes renewable hydrogen production. The government also plans to offer a 10-year production tax incentive of AUD 2/kg H_2 (USD 1.4/kg H_2) starting in 2027 for facilities operational by 2030. In 2021, the Australian government announced an AUS 539.2-million investment in clean hydrogen and CCS/CCUS technologies in its 2021-2022 budget.

Opportunities for growth

Australia is set to add over 50 GW of renewable energy capacity between 2024 and 2030, largely in solar PV installations. Utility-scale solar PV is forecast to represent 30% of renewable energy capacity by 2030 and distributed PV systems around 32%. State and federal-level auctions, corporate demand for renewable energy, and government targets (including a recent expansion of the CIS, a competitive auction mechanism to support 32 GW of renewables such as solar, wind, and battery storage) are fuelling interest in utility-scale systems.

Distributed solar PV capacity is expected to expand nearly 14 GW between 2024 and 2030, propelled by local remuneration policies for surplus solar energy exports, low system costs and high energy prices. However, new additions in distributed solar PV capacity will diminish towards 2030 due to market saturation, new rules for supplying energy to the grid, and declining compensation, reducing renewable energy capacity additions overall. For utility-scale wind and solar PV, state and local-level auctions or agreements to meet state targets and deploy capacity in REZs, along with corporate power purchase agreements with state agencies or retailers, will stimulate growth.

Several factors hinder faster expansion. Curtailment has been increasing since 2017 due to grid constraints. Moreover, in some areas, it can take years to connect a project to the grid post-completion, affecting project economics and causing delays. Tenders that award grid access rights in REZs are therefore being used to address connection issues.

Brazil

Policy analysis

Brazil aims to achieve climate neutrality by 2050, a goal reaffirmed in its 2023 Nationally Determined Contribution submission. Its renewable energy sector is highly developed, with renewables fuelling almost 90% of its electricity generation. In fact, Brazil has already surpassed its renewable electricity generation target of 84% by 2030.

The Auctions for Renewable Energy Support programme, launched in 2004, encourages the development of new renewable energy projects through competitive bidding. These auctions have successfully reduced the cost of renewable energy, making it competitive with traditional energy sources, and have attracted substantial investment in the sector. In January 2022, Brazil passed an updated Distributed Generation Law that formalises net-metering policies, enabling consumers to generate their own electricity from renewable sources and receive credits for excess electricity fed back into the grid.

Meanwhile, the National Bank for Economic and Social Development (BNDES) has established a specialised loan programme with conditions favouring the development of carbon-neutral projects. For instance, in 2023, BNDES approved financial support for multiple wind projects and solar PV projects, and it co-financed the development of a biogas plant.

Brazil's policy actions, including new energy auctions and market deregulation, have spurred a surge in renewable energy projects aiming for grid connection by 2030. This rapid growth has led to longer connection queues and delays, especially in regions with high resource potential. To tackle this problem, in 2023 Brazil allowed stalled projects to exit the queue without penalty, freeing up 10 GW of capacity, and launched tenders for new transmission infrastructure, targeting completion between 2026 and 2028 to ease grid congestion and support more renewable energy system connections.

BNDES also provided a loan to complete the Angra 3 nuclear power plant, although expansion of the site has been delayed, with the expected completion date set for 2031 instead of the originally planned 2023. Additionally, Brazil is considering the possibility of small modular reactor deployment.

In 2023, the country unveiled its National Hydrogen Programme. Its three-year action plan (2023-2025) outlines goals, regulatory frameworks and investments to position Brazil as a global leader in hydrogen production. In partnership with the Ministry of Finance and with support from the Inter-American Development Bank and the World Bank, a USD 35-million investment plan was proposed for the Climate Investment Funds to develop hydrogen hubs. A recently approved Senate bill sets the GHG emission threshold for low-carbon hydrogen certification at 4 kg CO_2-eq/kg H_2.

Opportunities for growth

Brazil is projected to add nearly 110 GW of renewable capacity from 2024 to 2030, predominantly in solar PV (81%) and onshore wind power (16%). A rising amount of utility-scale capacity procured in the free market through bilateral contracts – in addition to sustained high demand for distributed solar PV despite the phaseout of incentives – has raised the capacity forecast.

The IEA expects government-led auctions to play a diminishing role in Brazil's utility-scale renewable energy growth in upcoming years. Long-term bilateral contracts between developers and industrial consumers, providing price certainty and helping corporate entities meet decarbonisation goals, are expected to drive nearly 90% of Brazil's utility-scale renewable energy expansion. Consequently, the volume of government-led auctions has been decreasing as bilateral contracts reduce demand growth for Brazilian utilities.

Although a 2023 policy change has reduced remuneration, Brazil's net-metering scheme continues to stimulate distributed solar PV additions. In fact, the drop in compensation has had only a minor impact on financing for renewable energy projects because system costs are still declining and electricity prices continue to rise. However, system integration issues – exacerbated by the growing penetration of variable renewable energy sources – are hampering renewable energy deployment by lengthening connection queues and project lead times.

Nonetheless, a tender for new high-voltage transmission lines was held in 2023, with another scheduled for 2024, and projects are to be completed by 2030. Timely commissioning of these projects could alleviate transmission constraints and facilitate further expansion. Moreover, rising electricity demand might bolster auction volumes, providing additional support for renewable energy growth.

Canada

Policy analysis

The Canadian Net-Zero Emissions Accountability Act, enacted in 2021, legally commits Canada to achieving net zero emissions by 2050. Canada therefore aims for 90% of its electricity generation to come from renewable sources by 2030.

To advance its clean energy transition, the government of Canada engages in strategic partnerships. Although the country lacks nationwide renewable energy auctions or other feed-in-tariff programmes, some provinces have established their own schemes. For instance, renewable energy auctions are in place in Alberta to support renewable energy deployment, and in 2023 Ontario launched major renewable energy source procurements to acquire 5 000 MW of new wind, solar and other forms of renewable energy. Quebec's 2030 Plan for a Green Economy also involves expanding wind energy generation in remote areas. Meanwhile, in the Northwest Territories the government provides financial support for community-led clean energy projects that aim to help communities reduce dependence on diesel fuel for heating and power. The Canada Infrastructure Bank distributes additional financing to support renewable energy generation, transmission and storage.

Internationally, the 2023 memorandum of understanding between Canada and South Korea emphasises co-operation on critical minerals and the energy transition. This agreement focuses on topics such as trade and investment in mineral supply chains, the energy transition and energy security, information exchange, clean fuels such as hydrogen, and carbon capture, utilisation and storage technologies. The Canadian government has also announced investment tax incentives to further support carbon capture, utilisation and storage technology development.

Concerning hydrogen, Canada is conducting a competitive pilot auction and has introduced a tax support scheme to boost hydrogen production and manufacturing. In 2024, ammonia equipment became eligible for a tax credit of 15-40%, depending on the lifecycle emissions of the hydrogen produced at the specific site. Additionally, the country completed its Canadian Hydrogen Codes and Standards Roadmap in 2024, aligned with its hydrogen development priorities.

Opportunities for growth

Canada is expected to add nearly 25 GW of renewable capacity from 2024 to 2030, predominantly in onshore wind projects and utility-scale solar PV systems. Following the introduction of federal tax incentives and new competitive auction plans in several provinces, Canada has been making significant progress in meeting its climate goals. Certain provinces have even set specific renewable energy targets: Alberta has surpassed its aim to produce 30% of its electricity from renewables by 2030, while Saskatchewan is working towards achieving a 50% renewable electricity share by the same year.

Alberta, with its liberalised electricity market, plays a crucial role in Canada's renewable energy expansion, responsible for nearly half of forecast development. The province's openness to merchant projects and corporate power purchase agreements provides a unique growth avenue within Canada. However, Alberta's renewable energy development has encountered regulatory hurdles, such as a recent six-month moratorium on new projects and ongoing restrictions on developments in prime agricultural and protected areas. While these limitations may affect some projects, continued support for clean energy through tax credits, provincial targets and additional procurement plans offers substantial growth opportunities.

The need to reinforce grid infrastructure and shorten lead times are major challenges impeding Canada's low-carbon electricity mix expansion. For instance, obtaining approval from the federal government for a new electricity generation project takes over four years, while new transmission lines require more than three. Additionally, gaining social acceptance and community support in affected areas remains one of the main obstacles to higher capacity additions in Canada. Infrastructure limitations, particularly in the northern provinces, and the legacy of fossil fuel dependency in remote areas pose further challenges for renewable energy adoption in these regions.

For nuclear energy development, the Nuclear Energy Leadership Table unites federal and provincial governments with industry representatives to provide advice and set priorities. As Canada already has an advanced nuclear energy industry, it aims to use this potential to decarbonise its energy system. Indeed, the province of Ontario has announced plans to begin predevelopment for an additional 4.8 GW of capacity, and Canada has reaffirmed its commitment to small modular reactor technology as a key component of its energy strategy. Specifically, Ontario plans to deploy four more 300-MW Hitachi BWRX units from GE Hitachi Nuclear Energy at its Darlington site, which is expected to provide 1.2 GW of nuclear capacity by 2036 with small modular reactors. Additionally, New Brunswick Power has proposed installing more units at Point Lepreau, and Saskatchewan has been awarded public funding to support preparations for deploying Hitachi BWRX units.

China

Policy analysis

China has pledged to achieve carbon neutrality before 2060, and in 2020 it declared that it aims to peak carbon dioxide emissions by 2030. In 2022, the National Energy Administration released its 14th Five-Year Plan for Renewable Energy, targeting an 18% share of electricity generation from non-hydropower renewables (wind, solar, biomass and geothermal) by 2025, with all renewables reaching a 33% share.

The Chinese government is phasing out the feed-in tariffs that have supported wind and solar deployment for the past ten years. Starting in 2021, most PV and onshore wind projects ceased to receive these tariffs nationally. However, offshore wind and concentrated solar power projects still benefit from provincial feed-in tariffs. Developers of wind and solar PV projects are offered 15- to 20-year power purchase agreements at provincially set benchmark electricity prices, mostly determined by coal-fired generation.

Several policy and market trends are set to double renewable energy capacity expansion over the next five years. First, huge solar PV module production growth has led to significant cost reductions, and interest rates in China have been declining since January 2023, propelling the deployment of capital-intensive projects.

Second, recent power market reforms and the introduction of green certificate systems have enabled some utility-scale solar PV and wind developers to secure more attractive prices than those offered by regulated contracts. The energy regulator has also clarified rules for green energy certificates, with demand for these certificates on the rise. Developers in resource-rich areas can generate additional revenues by selling green power to other provinces.

Third, the central government's Whole County PV pilot policy, which mandates the equipping of a percentage of rooftops with PV panels, is further accelerating deployment. This project encapsulates provincial financial support for small-scale residential installations, which continue to receive national feed-in price premiums, albeit from a significantly reduced budget.

Preferential loans and development bank initiatives also aim to promote development in Western China by advancing new coal projects, oil and gas pipeline infrastructure, and west-east power transmission lines. In 2020, the government set three main goals for 2025: to enhance laws, standards and policies for green energy production and consumption; to create an institutional framework with both incentives and constraints; and to fully implement green production and consumption practices in key areas, sectors and processes.

In 2023, China produced 28 Mt of hydrogen, nearly 30% of the global total, with almost 60% from unabated coal and 25% from unabated gas, resulting in emissions of nearly 400 Mt CO_2. Despite this, China leads in global hydrogen deployment, particularly for electrolysis projects, synthetic fuel production, industry use and road transport. The 2022 national Hydrogen Industry Development Plan targeted 100-200 kt H_2 of production per year, but electrolytic hydrogen production from projects under construction could actually reach 470 kt H_2/year by 2024, surpassing national targets and approaching 40% of provincial goals.

China is also expected to commission more than half of new global ammonia capacity in 2024, with major projects in Inner Mongolia, where targets for low-emission hydrogen production are 2.5-5 times the national goals. However, development rights for 13 of its 31 approved green hydrogen projects (totalling 1 GW of electrolysis) were revoked in December 2023.

Additionally, in December 2023, Hebei province approved a 737-km hydrogen pipeline from Zhangjiakou Kangbao to Caofeidian port, set to begin construction in 2024 and become operational by 2027, at an investment cost of CNY 6.1 billion (USD 845 million).

Opportunities for growth

China's renewable energy capacity is projected to expand 3.2 TW from 2024 to 2030, tripling growth of the previous six years. Solar PV will lead this surge, accounting for 80% of the increase. Lower solar PV module costs resulting from overproduction, combined with recent declines in interest rates, have made solar PV highly competitive with coal-fired power. China's domestic solar PV market is essential for absorbing surplus capacity, as trade barriers are restricting exports to some large markets. Moreover, power market reforms and green certificate trading have given developers access to higher revenues, especially in regions with active wholesale markets, where prices often surpass regulated levels.

However, rapid solar PV and onshore wind expansion is expected to create grid integration challenges for new utility-scale and distributed PV projects, affecting project economics in the medium term. In the northern and northeastern provinces, rising curtailment is anticipated to reduce project bankability, especially as more capacity is deployed in these grid areas. Renewables-favourable electricity market reforms and green energy certificate trading among provinces could help alleviate system integration issues. Nonetheless, the potential for further acceleration remains limited, as China's current growth trajectory already suggests it will surpass most of its announced renewables-related targets.

Additionally, the government plans to expand its nuclear power plant fleet to propel "effective investment, enhance energy support, and reduce greenhouse gas emissions." China's nuclear power growth in the last decade has been remarkable, with capacity expansions of approximately 34 GW – nearly two-thirds of its existing nuclear capacity.

The country currently has 29 reactors, with a total capacity of 33 GW of nuclear power in various stages of construction. Aligned with its 14th Five-Year Plan, the country is targeting total installed nuclear capacity of 70 GW by 2025. This commitment is further underscored by its strategic aim to enhance self-sufficiency in its nuclear fuel cycle. With substantial domestic uranium reserves announced, China intends to procure one-third of its uranium from domestic sources and through equity stakes in African mining ventures. Moreover, it achieved a significant milestone with the commercial launch of its first fourth-generation reactor at the Shidaowan plant in December 2023.

European Union

Policy analysis

The European Union aims to achieve climate neutrality by 2050, targeting a net greenhouse gas emission reduction of at least a 55% by 2030 compared to the 1990 level. This goal is enshrined in the European Climate Law, and the European Union has adopted the new Renewable Energy Directive, raising the 2030 target for renewable energy in final energy consumption from 32% to 42.5%, with an aspiration to reach 45%.

For industry, the directive aims to increase the renewable energy share by 1.6% annually, with specific targets for sourcing 42% of hydrogen from renewables by 2030 and 60% by 2035. For buildings, the renewable energy target is 49% by 2030, with annual increases of 0.8% until 2026 and 1.1% through 2030.

The EU Action Plan for Grids, published in November 2023, emphasises the critical role of electricity grids in supporting a more decentralised, digitalised and flexible system. To address capacity needs and ageing infrastructure, measures include implementing projects of common interest; improving investment incentives through regulatory clarity; accelerating permitting; and promoting funding for smart grids and distribution networks. Long-term grid planning will be enhanced by facilitating communication among transmission system operators (TSOs), distribution system operators (DSOs) and generators.

In 2022, the European Commission unveiled the REPowerEU Plan, outlining measures to significantly reduce EU reliance on Russian fossil fuels by expediting the clean energy transition. The plan focuses on three key pillars: conserving energy; generating clean energy; and diversifying EU energy sources. It also encourages the combining of investments and reforms.

Nuclear power is acknowledged as a low-carbon energy option within the EU energy portfolio. Nonetheless, each member state retains autonomy in determining its own energy strategies, including for nuclear energy adoption.

In May 2024, the European Council adopted the Hydrogen and Decarbonised Gas Package, which defines hydrogen as low-carbon if it is generated with 70% less GHG emissions than the fossil fuel benchmark. The European Commission also approved 33 projects in 7 member states under the IPCEI Hy2Infra project, committing EUR 6.9 billion of public funding to deploy 2 700 km of hydrogen pipelines by 2027-2029, with an expected EUR 5.4 billion of private investment.

Opportunities for growth

The European Union is projected to add approximately 550 GW of renewable energy capacity between 2024 and 2030. Distributed solar PV systems account for the largest share of new installations, at about 40% of the total. Utility-scale solar PV makes up around 30% of the additions, while onshore wind installations contribute about 20%. Offshore wind projects, though proportionally smaller, will still play a significant role, accounting for roughly 5% of new capacity.

However, several administrative and regulatory barriers inhibit renewable energy expansion in the European Union. Lengthy and complex procedures for obtaining permits and regulatory approvals, coupled with high grid connection costs, create significant hurdles. Other economic and financial challenges also impede progress. For instance, the high upfront capital costs of renewable energy projects make their bankability dependent upon the cost of capital. EU renewable energy deployment trajectories are therefore diverse, as project bankability is linked to each member country’s particular funding mechanisms and economic conditions.

Weak grid infrastructure and social acceptance present further obstacles. Inadequate grid capacity and connectivity limitations restrict integration efforts, as do insufficient investments to modernise infrastructure to accommodate variable renewable energy sources. Opposition from local communities, and public concerns over environmental and visual impacts, also pose significant challenges. Nevertheless, the European electricity market’s high level of integration enhances the flexibility of interconnected markets to accommodate an increasing share of dispatchable renewable energy sources.

France

Policy analysis

The French government aims to achieve carbon neutrality by 2050. As outlined in its 2024 National Energy and Climate Plan (NECP), low-carbon energy sources should make up 58% of the total energy mix by 2030 and 71% by 2035. However, the country's electricity generation mix already includes about 90% low-carbon electricity sources. Compared with the previous NECP, the 2024 version raises the solar PV target to 54-60 GW by 2030 and slightly lowers ambitions for onshore wind (to 33-35 GW) and offshore wind (to 3.6 GW).

The primary driver of renewable energy expansion in France is government-led contract-for-difference auctions, which cover a significant portion of total capacity growth. Various factors contribute to renewable energy growth (particularly of solar PV), including adjustments to indexation mechanisms and regulations mandating renewable energy or rooftop vegetation integration into new or renovated non-residential buildings. This regulation creates opportunities in the growing market for power purchase agreements, though administrative feed-in tariffs for small-scale projects are expected to incite the majority of distributed developments throughout the forecast period.

Rising electricity tariffs have also spurred interest in residential and small commercial PV installations, with self-consumption becoming increasingly popular. However, project lead times in France remain longer than the European average, resulting in higher development costs and project cancellations. The French Renewable Energy Acceleration Bill aims to address these challenges by streamlining permitting processes, improving grid connections, and enhancing social acceptance through profit-sharing schemes. The bill's impact on the forecast remains uncertain, however, pending effective implementation and data on the status of projects awaiting grid connection.

Furthermore, the French government supports renewable energy innovation through the France 2030 Investment Plan. Among the projects this programme aims to support are floating wind farms and the development of decarbonised hydrogen technologies. It has also dedicated EUR 900 million (USD 976 million) in grants to support industrial investments in renewable hydrogen and biomass, with a 36-month project completion timeline.

Opportunities for growth

France is set to add around 50 GW of new renewable energy capacity during 2024-2030 owing to strong participation in recent onshore wind tenders and accelerated growth in distributed solar PV, spurred by new regulations for commercial installations and rising electricity tariffs. In fact, if these policy updates are implemented swiftly, demonstrate effectiveness and achieve high subscription rates in future tenders, France's new capacity additions from 2024 to 2030 could exceed 50 GW. This potential increase also hinges on successfully implementing training programmes to address shortages of skilled PV installers amid accelerated deployment, and on adapting management strategies for dispatchable energy sources to better align them with variable renewable generation patterns and reduce curtailment.

In the nuclear energy sector, in 2022 France unveiled intentions to build six new European Pressurised Reactors at an estimated cost of EUR 51.7 billion (USD 52.73 billion), with the final investment decision expected in early 2026. The country is concurrently embarking on a substantial initiative to prolong the operational lifespan of its current reactor fleet, which has an average age of 37 years. Furthermore, France has committed EUR 1 billion to foster the development of commercially feasible small modular reactors until 2030 – a pivotal component of its announced nuclear strategy.

Germany

Policy analysis

As outlined in its amended Climate Change Act, the German government has pledged to achieve net zero emissions by 2045 and aims to secure 80% of its electricity from renewable energy sources by 2030. Capacity targets for 2030 are 215 GW for solar PV and 115 GW for onshore wind. In 2023, Germany finished phasing nuclear energy out of its energy portfolio, transitioning away from its use entirely.

Ambitious targets, competitive auctions and supportive policies such as feed-in tariffs and premiums are driving renewable electricity growth. Corporate procurement, especially from large industrial consumers facing high electricity prices, has also contributed to expansion in utility-scale projects. Additionally, households have received financial support to install small-scale solar PV systems.

In 2022, higher costs and low maximum contract prices made utility-scale solar PV auctions challenging. In response, the government adjusted ceiling prices to accommodate inflation, leading to full subscriptions in subsequent auctions. Meanwhile, reforms to reduce permitting times for onshore wind have been under way since 2021. They include the Onshore Wind Act, which mandates that federal states allocate an average 2% of their land to onshore wind development by 2032, and amendments in the Special Species Protection Act.

Meanwhile, the German government offers energy-intensive sectors financial support through its carbon contracts for difference (CCfD) programme. The primary objective of this initiative is to expedite the shift away from fossil fuels in energy-intensive industries by making it easier to transition to greener alternatives in production processes, for example by establishing hydrogen production facilities and retrofitting pipelines. The first round of CCfD contracts offered EUR 4 billion (USD 4.4 billion) of support over 15 years.

In 2023, Germany outlined plans for three hydrogen-capable power plant tenders totalling 24 GW, but by July 2024 this target had been revised to 12.5 GW under its power plant strategy. The initial phase includes tenders for 5 GW of new hydrogen-ready gas plants and 2 GW of retrofitted capacity, requiring a switch to hydrogen after eight years of operation. Successful bidders will receive capital and operational subsidies covering the cost gap between natural gas and hydrogen for up to 800 hours annually. Additional support for 500 MW of hydrogen-only capacity is also planned, with the first tenders expected in early 2025. A second phase could offer another 5 GW of capacity if the policy is maintained.

Opportunities for growth

Germany is set to more than double its installed renewable energy capacity by 2030, adding 185 GW to reach a total of 359 GW.

Solar PV will lead growth, with an increase of 129 GW bringing total capacity to 212 GW by 2030, nearly meeting the targeted 215 GW. Distributed solar PV will account for a significant portion, with policies from 2022 incentivising systems that export all generated electricity to the grid, spurred by rising energy costs following geopolitical events. Though residential system growth slowed in early 2024, the forecast for distributed PV remains strong owing to consistent incentives and overall demand for renewable energy.

Onshore wind will also expand substantially, benefiting from permitting reforms that have increased annual permit approvals. As a result, Germany expects onshore wind capacity to reach 100 GW by 2030. However, achieving the 115-GW target will require further electrification initiatives to balance increased variable renewable energy inputs. Offshore wind additions of 13 GW are expected, aiming for 21 GW by 2030, with further growth anticipated beyond 2030 as new projects come online from the current tender pipeline. Although project lead times introduce some uncertainty, recent progress in permitting and the government’s centralised auction approach offer a promising outlook.

India

Policy analysis

At the 2021 COP26 climate summit, India announced its goal to achieve net zero emissions by 2070. It aims to source 50% of its installed power capacity from non-fossil fuel-based energy resources by 2030, corresponding to an additional 500 GW of stock additions compared with the 2022 level.

The more ambitious auction schedule India introduced recently is propelling current renewable energy growth, with utility-scale solar PV in the lead and onshore wind installations expected to recover from the past five years' slowdown. The adoption of closed-envelope auctions and an increase in hybrid PV-wind projects are set to push deployment past the record set in 2017.

Central and state-level public entities and utility companies (DISCOMs) are the main drivers of renewable capacity deployment in India. In the first half of 2024 alone, 33 GW of capacity were awarded in capacity auctions, surpassing capacity awards for the whole of 2023. Additionally, hybrid auctions that integrate PV, wind and storage technologies to facilitate smoother system integration accounted for 40% in 2024. This promising trend has the potential to address numerous challenges associated with rising variable renewable energy penetration.

The Indian government's mandate for public entities to auction 50 GW per year will also boost utility-scale solar PV and wind deployment. Furthermore, some energy from solar PV, wind, pumped-storage hydropower and battery energy storage is exempted from interstate transmission system fees.

Concerning hydrogen development, Indian projects must not exceed the National Green Hydrogen Standard of 2 kg CO_2-eq/kg H_2. INR 11.65 billion (USD 140 million) will subsidise 550 kt/year of renewable ammonia production over three years, and India has also allocated INR 2 billion (USD 24 million) for FY2025-2026 to establish at least two renewable hydrogen hubs with a minimum capacity of 0.1 Mt/year. A 5-15% renewable hydrogen quota for the refining sector will be introduced from FY2026-2027, with regulations under stakeholder consultation.

For electrolyser manufacturing, India has committed INR 44 billion (USD 0.5 billion) for FY2025-2026 to FY2029-2030, following the successful 2023 auctioning of 1.5 GW/year of capacity. An additional tranche of 1.5 GW/year was launched in early 2024, with incentives declining over five years. India has also earmarked INR 4 billion (USD 48 million) to support domestic technology development, to cover up to 80% of project costs.

The International Hydrogen Trade Forum (IHTF), initiated during the 2023 G20 meeting, has partnered with the Hydrogen Council to prioritise cross-border trade, share best practices and facilitate ongoing dialogue through an annual roundtable.

Opportunities for growth

India's renewable energy capacity is forecast to increase 350 GW between 2024 and 2030, nearly tripling the 2022 level to reach over 550 GW. This aligns India with the COP28 global pledge to triple renewable capacity and supports its national goal of 500 GW of non-fossil energy by 2030. Accounting for 60% of new additions, auction-driven utility-scale solar PV dominates growth, bolstered by record auction volumes in early 2024 and a new rooftop PV support scheme.

Distributed solar PV is also set for robust growth, particularly in the commercial and industrial sectors, benefiting from open-access grid rules. A new support scheme targeting 30 GW of residential rooftop PV additions by 2027 is expected to increase distributed PV capacity nearly fivefold by 2030. Further supporting this expansion are the Renewable Purchase Obligation for FY 2024-2025, which now includes distributed systems, and the improved financial health of India's DISCOMs. Although financial challenges persist for many DISCOMs, ongoing government interventions have stabilised their performance, enhancing their capacity to support renewable energy projects.

In terms of wind energy, India's latest auction rules are expected to ease financial pressure for developers, though land acquisition and grid connection remain barriers to wind capacity growth. Most wind expansion is anticipated to come from hybrid projects, as offshore wind auctions are in the early stages and are unlikely to produce operational plants before 2030. Achieving India's ambitious renewable energy targets will also require cohesive policy co-ordination to strengthen its domestic PV supply chain, particularly given the recent trade restrictions requiring auctioned projects to source modules from government-approved manufacturers only.

Regarding nuclear energy, the National Electricity Plan 2023 projects approximately 13 GW of new nuclear capacity by 2032, with several reactors currently under construction. Additionally, the government has revealed plans to collaborate with the private sector to develop small modular reactors.

Indonesia

Policy analysis

Indonesia's goal is to achieve net zero emissions by 2060 or earlier, but it revised its renewable energy target downwards in 2024 to 19-21% by 2030. Although Indonesia has considered developing nuclear power plants, it has not yet committed to nuclear energy and is currently focused on expanding its renewable energy sources.

The Just Energy Transition Partnership, launched in 2022, is likely to be a key driver of renewable energy deployment. This international initiative provides around USD 20 billion in funding to accelerate Indonesia's energy transition through concessional financing for strategic investments in the energy sector. In 2023, the government announced financial support to cover the upfront costs of low-carbon energy systems for households in isolated areas without access to the main power grid.

Like Japan and China, Indonesia has successfully demonstrated ammonia co-firing in coal-fired power plants. The direct use of 100% ammonia was successfully demonstrated in a 2-MW gas turbine in 2022, with ongoing efforts to scale up to larger gas turbines, potentially reaching 400 MW by 2030. IHI and GE Vernova are collaborating on retrofittable ammonia combustion systems for existing gas turbines, with plans to test these systems in Singapore. In October 2023, Singapore's Sembcorp Utilities and Indonesia's state-owned utility PLN signed a joint development study agreement to assess the feasibility of an offshore hydrogen pipeline connecting Indonesia to Singapore.

Opportunities for growth

Indonesia's renewable energy capacity is expected to grow 22 GW from 2024 to 2030, a nearly fivefold increase from the previous seven years. Utility-scale solar PV will lead this expansion, with distributed PV and hydropower also contributing significantly. Bioenergy and geothermal capacity are expected to expand roughly 40% from the 2023 level by 2030.

A 2022 presidential decree establishing a supportive policy framework to accelerate renewable technology deployment is shaping the country's renewable energy landscape. However, delays in formulating regulatory details and procurement processes have tempered short-term expectations, making it likely that Indonesia will fall short of its 2030 renewable energy targets without stronger policy support.

Indonesia is also facing challenges in integrating new renewable energy capacity due to existing long-term contracts with coal and gas power plants, as well as overcapacity issues. In fact, the Java-Bali power system reserve margin exceeded 75% in 2022, limiting opportunities for new renewable capacity additions until at least 2030. Despite these hurdles, however, Just Energy Transition Partnership funding and policy improvements could give Indonesia's renewable energy ambitions critical momentum.

In the nuclear energy sector, in 2024 the Indonesian government announced its intention to build 20 nuclear power plants. The first 500-MW thorium molten salt reactor is to be operational by 2028.

Italy

Policy analysis

Italy aims to achieve carbon neutrality by 2050 and has set its renewable energy target at 55% of electricity generated by 2030. The country does not have nuclear power, as the Italian public rejected it in a 1987 referendum, leading to the closure of existing nuclear plants and a ban on the construction of new ones. However, Italian companies are actively exploring small modular reactor potential.

Renewable energy auctions support renewable energy development. However, in February 2023 the government announced plans to gradually reduce the 110% tax credit (Superbonus) introduced in 2020 for residential solar PV investments. This prompted a surge in installations in 2023 as homeowners rushed to capitalise on the more favourable incentive. While residential PV deployment is expected to decelerate in 2024, it is anticipated to remain above the 2021 level. Simultaneously, commercial installations have been on the rise because of escalating electricity prices. Increased consumer confidence in the economic and energy security benefits of rooftop solar PV is expected to fuel significant growth.

The Italian government has also issued a consultation document outlining incentives for renewable hydrogen, setting a demand target of 0.25 Mt/year by 2027. At least 80% of this is to be met by domestic production, which will require 3 GW of electrolysis capacity. Italy has therefore initiated two-way contracts for difference and annual auctions from 2024 to 2027, targeting 250 kt/year of renewable hydrogen by 2027 and 50 kt/year of hydrogen from bioenergy through 10-year contracts.

Italy has also announced EUR 2 billion (USD 2.2 billion) for the technological development of renewable hydrogen used in industrial heat and steel production, and EUR 1.1 billion has been allocated to the manufacturing of clean technologies, including electrolysers, with grants available before 2026. Furthermore, Italy is involved in the SouthH_2 Corridor project, linking Europe with North Africa as part of the European Hydrogen Backbone initiative.

Opportunities for growth

Italy is on track to add 56 GW of renewable energy capacity between 2024 and 2030 – a quadruple increase from the previous seven years. Distributed solar PV will make up over half of this growth, with rooftop installations soaring to 4 GW in 2023. This rise, spurred by reductions in tax credits and high electricity prices, gives Italy a strong outlook and positions it close to achieving its National Energy and Climate Plan targets for 2030. However, the country's complex permitting processes might cause a slight shortfall in wind deployment.

Delays have hampered the effectiveness of Italy's current auction system, launched in 2019, with permitting obstacles making 14 rounds necessary to allocate 5.5 GW of planned PV and onshore wind capacity. The government therefore prepared a revised auction model with higher ceiling prices in 2024, aiming to award 40 GW of PV, 16.5 GW of onshore wind and 10 GW of smaller renewables by 2028.

Success will depend on continued permitting improvements, however, as Italy has nearly 30 GW of PV and 20 GW of wind projects nearing connection. About 350 GW are at the application phase, presenting a grid connection challenge.

Sustained rooftop solar PV demand reflects increasing consumer confidence in its economic and energy security benefits, setting the stage for robust distributed PV growth throughout the forecast period.

Japan

Policy analysis

In 2020, the Japanese government announced Japan's goal to achieve carbon neutrality by 2050. The country therefore plans to raise the share of renewable energy in its energy mix to 36-38% by 2030.

The government has been offering competitive feed-in premiums for renewable energy projects since 2022, and newly established feed-in premiums for commercial and residential power consumers will boost solar PV installations by promoting capacity additions. Furthermore, the Basic Policy for Green Transformation aims to accelerate solar PV installations in public buildings. New policy initiatives also seek to strengthen grid investment over the next decade, and the government's Green Innovation Fund financially supports companies working on renewable energy industry innovations.

Japan also supports the use of nuclear energy and intends to restart its nuclear power plants, aiming for nuclear power to provide 20-22% of the electricity supply by 2030. Although the restart of the Japanese nuclear power fleet has been promoted, the construction of new nuclear power plants has not been launched. Nevertheless, the country is involved in small modular reactor development, and in February 2023 the Japanese government endorsed a policy to develop and construct next-generation innovative reactors, including small modular ones.

Owing to government initiatives in Japan and Korea to decarbonise power generation using hydrogen and ammonia, these countries hold almost all the world's hydrogen offtake agreements for power generation. Five coal-fuelled plants planning to co-fire ammonia (770 MW combined capacity, averaging 19% ammonia co-firing for 4 100 MW of coal capacity) and one 55-MW gas plant in Japan were awarded OPEX funding. This follows Japan's 2023 Hydrogen Society Promotion Act, which allocated USD 20 billion to 15-year contract-for-difference subsidies for hydrogen production.

Under the Hydrogen Society Promotion Act, Japan's GHG emission thresholds of 3.4 kg CO_2-eq/kg H_2 for hydrogen and 0.87 kg CO_2-eq/kg NH_3 for ammonia align with EU and US standards. The country's ENE-FARM project had also deployed over 500 000 fuel cell micro co-generation units by the end of 2023, despite a 20% decline in annual installations. In June 2024, Jera completed a three-month trial of 20% ammonia co-firing at its 1-GW Hekinan coal plant.

Opportunities for growth

Japan's renewable energy capacity is projected to expand 75 GW from 2024 to 2030, reaching a total of 246 GW (DC), aligned with its solar PV target of 187 GW (AC) by 2030. Solar PV is expected to make up 75% of this growth, although annual installations may decline as Japan phases out its feed-in-tariff scheme in favour of a competitive feed-in premium that supports steady growth through self-consumption in the commercial and residential sectors.

Further shaping the country's renewable energy landscape is a new auction system launched in January 2024 for long-term energy decarbonisation. The scheme covers utility-scale batteries, and the first auction awarded more than 1 GW of battery capacity. This auction mechanism, along with policy initiatives targeting an eightfold increase in grid investments over the next decade, is set to enhance renewable energy integration and grid stability.

While solar dominates Japan's renewable energy profile, the country's 2024 review of its 7th Basic Strategic Energy Plan reflects a growing emphasis on energy mix diversification. Onshore and offshore wind are gaining ground, with more than 4.5 GW of offshore capacity expected from government auctions, boosted by subsidies and streamlined permitting processes. However, social acceptance, infrastructure expansion and environmental permitting challenges continue to slow deployment, particularly for wind energy projects that have long lead times.

Japan is also positioning itself as a global leader in green hydrogen through comprehensive policies and significant investments. With its Hydrogen Society Promotion Act and CCS Business Act, it aims to provide subsidies and regulatory support for low-carbon hydrogen adoption in industry, especially in hard-to-electrify sectors such as heavy transport and manufacturing.

The Japanese government is therefore investing strongly in green hydrogen technologies to reduce costs and scale up production, including through a dedicated fund of JPY 2 trillion (around USD 20 billion) to support green technology and hydrogen R&D. Japan's hydrogen market is projected to grow at a rapid pace, with significant uptake in the transport and power generation sectors expected by 2030. These initiatives reflect Japan's commitment to create a robust hydrogen supply chain, reduce reliance on imported fuels, and make hydrogen a cornerstone of its decarbonisation and energy security strategy.

Korea

Policy analysis

As mandated by its Carbon Neutrality Act of 2021, Korea has pledged to reach net zero emissions by 2050. The Korea Renewable Energy 3020 Plan therefore targets 20% energy generation from renewable energy sources by 2030.

The K-RE100 initiative, which focuses on corporate procurement of renewable energy, remains pivotal for expanding utility-scale wind and solar PV installations over the next five years, with renewable energy certificates boosting project bankability.

Meanwhile, renewable portfolio standards support distributed PV expansion in the residential and commercial sectors. Furthermore, Korea's first large-scale offshore wind projects are expected to become operational by 2028, thanks to auction programmes, national incentives and municipal government support.

Twenty-six nuclear reactors currently meet one-third of electricity demand in South Korea, and in 2023, construction contracts were awarded for the Shin Hanul 3 and 4 power plants. New reactors are to be completed by 2032 for unit 3, and by 2033 for unit 4. According to Korea's 10th Basic Plan, published in January 2023, nuclear will represent almost 35% of electricity generation by 2036 owing to the startup of six new reactors. This plan also outlines Korea's intention to export ten nuclear units by 2030 and to develop its own small modular reactor. At the G7 summit in May 2023, a consortium from Japan, Korea and the United States announced co-operation on funding the deployment of a small modular reactor in Romania.

In the hydrogen sector, the Korean government has announced tax credits of up to 25% for hydrogen projects and 12% for fuel cell manufacturing facilities, and a further tax incentive of up to 50% for clean hydrogen production is under consideration. Korea has implemented 15-year contracts for 6.5 TWh/year of power generation starting in 2028, covering 100%-hydrogen facilities, hydrogen co-firing in gas plants, and ammonia co-firing in coal plants.

The auction, which closed in November 2024, had a GHG emission threshold of 4 kg CO_2-e/kg H_2. A separate auction for 1.3 TWh of hydrogen-based power generation by 2026 without GHG criteria is also under way, contributing to Korea's 2030 target of 2.1% of electricity generation from hydrogen derivatives.

In late 2023, Hanwha successfully demonstrated 100% hydrogen firing in an 80-MW gas turbine, achieving nitrogen oxide emissions below 9 ppm without specialised flue gas treatment. Earlier that year, the company had achieved 60% hydrogen co-firing by volume. In June 2024, Korea announced a

USD 577-million plan to establish a hydrogen belt along the east coast, with a focus on developing a hydrogen pipeline network.

Opportunities for growth

Korea's renewable energy capacity is expected to grow 25 GW from 2024 to 2030 for a total of 66 GW, though this falls short of the country's target of 76 GW by 2030. The primary growth driver is corporate procurement of renewable energy, especially utility-scale wind and solar PV, which benefits from renewable energy certificates that enhance project bankability. For distributed solar PV, renewable portfolio standards incentivise expansion in residential and commercial installations.

Large-scale offshore wind is also anticipated to gain traction, supported by national and local incentives, certificates and the auction programme, marking the entry of these projects into Korea's energy mix for the first time. However, renewed emphasis on nuclear energy in the government's 10th and 11th Basic Plans for Electricity Supply and Demand has lowered overall solar and wind targets, slowing renewable energy capacity additions. The increasing importance of nuclear generation will limit solar and wind growth, with annual additions of 6 GW targeted to 2030.

Key challenges are an inadequate number of auctions, with some undersubscribed due to low reference prices, and long permitting and grid connection delays. If auction frequency and pricing improve, and if new policies raise social acceptance, streamline permitting, expand grid infrastructure and make power purchase agreements more affordable, renewable energy deployment could grow.

Mexico

Policy analysis

At COP29, Mexico announced the commitment to pursue a net zero economy by 2050. In 2024, Mexico set the ambition to reach 45% of electricity generation from renewable sources by 2030.

Renewable energy auctions, for both energy and capacity, facilitate renewable energy deployment in Mexico, and clean energy certificates and a net-metering scheme further accelerate renewable energy stock additions. The country has a considerable share of distributed solar PV installations because the permitting process for these systems is efficient. In contrast, utility-scale solar PV projects advance slowly because the permitting process is sluggish and there is no federal policy governing renewable energy procurement.

Mexico currently operates two nuclear reactors at the Laguna Verde plant with a combined capacity of approximately 1 600 MW. These reactors currently contribute only a fraction of the country's total electricity generation, and their operating licences were recently extended: Unit 1 to 2050 and Unit 2 to 2055. Although a 2022 government report projected a doubling of nuclear generation by 2035, indicating potential new nuclear capacity beyond Laguna Verde, no concrete policy or governmental steps to expand nuclear power have yet been taken. While discussions have touched upon the potential use of small modular reactors for both power generation and desalination in the long term, no solid plans have materialised.

In 2024, Mexico introduced its first hydrogen guidelines, and in March of that year Pemex released its 2050 sustainability plan, outlining its intention to begin importing hydrogen from the United States between 2030 and 2035, with domestic production slated to commence in 2035. However, Mexico's oil refining has fallen in the last decade, reducing overall hydrogen demand, and challenges in obtaining competitively priced natural gas for ammonia production have completely halted activity in this area.

Opportunities for growth

Mexico is projected to add nearly 20 GW of renewable energy capacity by 2030, with solar PV as the primary contributor, followed by wind. The new administration intends to maintain the prior government's policies, which emphasise renewable energy while supporting the state-owned utility, CFE. This approach is expected to allow Mexico to meet its 2030 renewable energy target.

For utility-scale projects, about 9 GW of solar PV and 3 GW of wind will be developed, led by the CFE and independent power producers through self-supply contracts, past auction allocations and the wholesale market. Benefiting from Mexico's net-metering scheme, distributed solar PV capacity is forecast to expand nearly 6 GW as lighter administrative requirements than for utility-scale projects enable faster deployment. However, Mexico's slow permitting process and its lack of a federal renewable energy procurement policy impede greater market growth.

Russia

Policy analysis

Russia aims to achieve carbon neutrality by 2060. To reach this goal, the country must increase the deployment of carbon-free energy sources significantly. As of 2022, nuclear power accounted for 19% of total electricity generation, hydropower for 17%, and variable renewables for only a marginal portion. At COP28, Russia declared its intention to double renewable energy capacity by 2030, from 6 GW to 12 GW.

To stimulate growth in the renewable energy sector, Russia has introduced renewable energy auctions and capacity-based investment incentives. Despite these efforts, fossil fuels – particularly natural gas – continue to dominate the country's electricity generation mix.

Nuclear power is a cornerstone of Russia's energy strategy. The country operates 36 nuclear reactors and has ambitious plans to expand its nuclear fleet, with several new reactors under construction and more planned for upcoming decades. In fact, Rosatom envisions nuclear power providing 45-50% of Russia's electricity by 2050.

Additionally, Russia is a major exporter of nuclear technologies and services globally, and expanding these activities is one of its primary policy and economic objectives. As a global leader in fast neutron reactor technology, it is advancing its Proryv project to construct nuclear plants that use fast reactors with a closed fuel cycle. It is also developing small and medium-sized power reactors, including floating power modules. Russia's first land-based small modular reactor project, the RITM-200 water-cooled unit at the Yakutia site, is currently under development and is expected to be completed by 2028.

In 2020, Russia introduced a roadmap for hydrogen development, targeting exports of 2 million tonnes by 2035. Since its invasion of Ukraine, however, these ambitions have been scaled back nearly 75%.

Opportunities for growth

Russia is projected to increase its renewable energy capacity 5 GW from the 2023 level by 2030, primarily through onshore wind and solar PV additions. The country's state-owned electricity utility is expected to initiate one-third of this development, while auctions and tenders cover the remainder.

Saudi Arabia

Policy analysis

Saudi Arabia aims to generate 50% of its electricity from natural gas and renewable sources by 2030 and achieve net zero emissions by 2060. It also intends to advance solar and wind energy projects to diversify its energy mix and reduce reliance on oil and gas. To these ends, it has launched several large-scale renewable energy initiatives, including the National Renewable Energy Program (NREP) and the Saudi Green Initiative. Under NREP, contracts for over 3.6 GW of solar PV capacity have been awarded through competitive auctions.

In May 2023, the government announced nearly 7 GW of signed power purchase agreements under its sovereign fund programme. Progress in hydrogen project development has also accelerated, with the flagship NEOM project reaching financial close in May 2023, accompanied by a 30-year offtake agreement for ammonia.

Although Saudi Arabia does not currently have operational nuclear power plants, it has shown interest in developing nuclear energy for electricity generation and desalination. It has signed agreements with several countries, including China, Japan, Korea and Russia, to co-operate on nuclear power development and technology transfer. These agreements also include potential small modular reactor deployment.

In October 2023, Topsoe and Aramco announced a partnership to construct a small modular reactor demonstration plant in Saudi Arabia dedicated to producing blue hydrogen. Additionally, the 2.2-GW NEOM Green Hydrogen project – currently the world's largest electrolyser project under construction – reached financial closure in May 2023 and aims to begin operations in 2026. Judging by this project, the estimated construction timeline for a GW-scale plant appears to be around three years from final investment decision (FID) to operational start. In the case of NEOM, however, construction commenced a few months pre-FID.

Opportunities for growth

Saudi Arabia is expected to expand its renewable energy capacity from under 2 GW to nearly 45 GW by 2030, thanks primarily to solar PV growth. Rising domestic energy demand and plans to diversify into hydrogen production for export drive this expansion. With Saudi electricity demand reaching a record 325 TWh in 2023, the government's push for renewable energy also aims to reduce reliance on oil-fired power generation, freeing up more oil for export.

Another component of the country's renewable expansion strategy targets power export opportunities. Its energy interconnections with Egypt are already 60% complete, potentially enabling renewable electricity exports, and Saudi Arabia and Greece are exploring options for Greece to import electricity.

Bilateral contracts with the Public Investment Fund (PIF) and the state utility spur a considerable proportion of Saudi Arabia's renewable energy growth (over half of new capacity), while competitive auctions for long-term power purchase agreements cover 27%. Renewable energy capacity dedicated to hydrogen production makes up nearly 10% of planned additions. Although the country's ambitious goal is to reach 58 GW by 2030, the current growth trajectory is on track for 45 GW, thanks to increased numbers of power purchase agreements and accelerated hydrogen project development under the PIF.

Two main impediments to achieving Saudi Arabia's forecast growth are the slow pace of project development and the lack of a long-term renewable energy policy beyond 2030. Despite the government's efforts to launch renewable energy auctions, slow implementation and delays in contract signings have hindered progress. As a result, only one contract has been awarded in Saudi Arabia, two years after the initial bidding in 2021. The pace of project development is a key forecast uncertainty, and while the government aims for a 50% share of renewable generation by 2030, no targets have been announced beyond this time frame. Additionally, the government has not formulated detailed plans to achieve its goal of net zero emissions by 2060.

South Africa

Policy analysis

As outlined in its Low Emission Development Strategy, South Africa aims to achieve net zero emissions by 2050. It therefore plans to increase the share of renewable energy in its total electricity mix to 41% by 2030.

Two main government policies to reduce load shedding and increase electricity generation capacity drive renewable energy capacity expansion. First, commercial and residential power consumers are being offered lower licensing thresholds to install renewables-based power plants for self-consumption, with the state utility company determining electricity tariff arrangements. This policy encourages power consumers to do their part in mitigating electricity supply disruptions.

Second, through its auctions for utility-scale projects, the government aims to replace decommissioned coal-fired capacity (although the initial target of phasing out coal by 2030 has been extended). Other factors driving renewable energy growth are the procurement of power and establishment of solar PV feed-in tariffs by municipalities, as well as investments by state-owned energy companies in new capacity to replace retiring facilities.

South Africa's Green Hydrogen Commercialisation Strategy, published in 2022 and approved by the cabinet in 2023, sets ambitious renewable hydrogen production targets of 1 Mt/year by 2030 (requiring 13 GW of electrolysis) and 4 Mt/year by 2050 (41 GW of electrolysis). It is anticipated that 50% of this production will be directed towards exports by 2040.

The government has announced potential tax benefits (e.g. accelerated depreciation, industrial policy allowances, exemptions from proceeds and import duty exemptions) to support renewable hydrogen projects, but they have yet to be formalised into law. Bilateral financing, for instance in "south-south" co-operation, exemplified by a USD 5-million loan from South Africa to a company developing hydrogen projects in Namibia, is also becoming popular.

South Africa currently operates two nuclear power reactors at the Koeberg site, with a combined capacity of 1.9 GW. Regulatory approval is pending to extend Koeberg's operating licence by 20 years, and in December 2023 the government disclosed intentions to initiate a bidding process by March 2024 to acquire an additional 2.5 GW of new nuclear capacity. The country also aims to become an exporter of small modular reactor technology, as multiple innovations have originated in South Africa.

Opportunities for growth

South Africa is projected to add 35 GW of renewable energy capacity by 2030, primarily from solar PV (nearly 80%) and onshore wind. Policies aimed at addressing electricity shortages and reducing load shedding spur this growth. Through auctions and private procurement, South Africa is positioned to exceed the 2030 targets outlined in its latest Integrated Resource Plan (IRP).

A key policy driving renewable energy uptake is the lowering of the country's licensing threshold to enable businesses and independent producers to install power plants for self-consumption or to provide wheeling capacity through the public utility, Eskom. Thanks to this policy change, corporations are expected to expand investments in utility-scale wind and solar PV to ensure power reliability. Additionally, past (2021-2023) and upcoming auctions for utility-scale projects aim to meet demand and replace retiring coal capacity, even though some decommissioning timelines have been delayed.

Other growth stimulants include municipalities procuring their own power; Eskom's plans to repurpose retiring coal assets; and international development collaborations. However, challenges persist, notably Eskom's financial constraints, which could impede necessary grid upgrades for renewable energy integration. In fact, grid capacity shortfalls have already impacted recent auctions, with no wind capacity awarded because of grid limitations in proposed areas. Additionally, high interest rates, inflation and commodity prices have slowed power purchase agreement signings, affecting project timelines. Passage of the Electricity Regulation Amendment Bill, aimed at liberalising the energy market, could further propel capacity expansion.

Türkiye

Policy analysis

Türkiye has pledged to achieve carbon neutrality by 2053, and its renewable energy target is set at 50% by 2030.

Türkiye's renewable energy auction scheme, YEKA, is designed to procure large-scale renewable energy projects through competitive bidding, ensuring low prices while promoting domestic manufacturing of renewable energy equipment such as wind turbines and solar panels. Winning bidders must establish local manufacturing facilities, fostering a domestic renewable energy industry supply chain. The YEKDEM feed-in-tariff scheme, introduced in 2005, has guaranteed prices for renewable electricity. Furthermore, the Green Climate Fund financially supports private and public climate projects.

In 2023, Türkiye launched its National Hydrogen Strategy and Roadmap, setting ambitious objectives and policy frameworks to establish itself as a key player in the global hydrogen market. The strategy includes targets for scaling up green hydrogen production, and the country aims to reduce the cost of green hydrogen to less than USD 2.4/kg by 2035, and to below USD 1.2/kg by 2053. To support these goals, Türkiye plans to increase its installed electrolyser capacity to 2 GW by 2030, 5 GW by 2035 and an ambitious 70 GW by 2053.

Opportunities for growth

Türkiye is anticipated to increase its renewable energy capacity more than 50 GW from 2024 to 2030. Solar PV installations are expected to constitute two-thirds of total capacity, with utility-scale systems marginally outweighing distributed ones. Onshore wind additions contribute around 18% to total renewable energy capacity expansion, while hydropower makes up approximately 10%.

Türkiye has announced the resumption of renewable energy auctions to boost clean energy investments and accelerate its transition to renewable energy sources such as solar, wind and biomass. Set to begin in early 2025, these auctions target both large- and small-scale projects to meet rising energy demand and cut fossil fuel reliance. Offshore wind projects will also receive attention, with coastal sites identified as potential locations for wind farms, contributing to Türkiye's long-term energy security and reducing dependence on imported gas.

The country's first nuclear plant, Akkuyu, is under construction by Russia's Rosatom and has four reactors. As Türkiye's long-term goal is to have over 20 GW of nuclear capacity by the 2050s, it plans to construct at least two additional conventional nuclear plants after Akkuyu. One of these may be developed by

China and the US-derived technology in the Thrace region, and the other by KEPCO at the Sinop site. Additionally, Türkiye is investigating the deployment and potential local manufacturing of small modular reactors through collaborations with France, the United States and the United Kingdom.

United Kingdom

Policy analysis

The United Kingdom intends to attain net zero emissions by 2050, a binding objective enshrined in its Climate Change Act. As part of this ambition, it aims to decarbonise its power sector by 2035.

While contract-for-difference (CfD) auctions continue to serve as the primary policy instrument supporting utility-scale projects, there was a distinct shift between 2022 and 2023 as high electricity prices led renewable energy system operators to explore financing beyond the CfD framework. The fourth auction round in 2022 was successful, allocating 7 GW of offshore capacity, but none of the estimated 4 GW of capacity in 2023 was allocated under this scheme. Additionally, a previously awarded 1.4 GW of offshore wind farm capacity from CfD round 4 was cancelled for similar reasons. Furthermore, elevated electricity prices have accelerated the deployment of distributed PV. Notably, projects supported by corporate power purchase agreements and wholesale power sales are anticipated to play an increasingly significant role in driving renewable energy deployment.

In a bid to counteract these challenges, the UK government announced a significant 66% tariff cap increase for offshore wind in auctions slated for 2024, expecting to bolster participation levels. Nevertheless, delays in CfD awarding processes and project cancellations pose a looming threat to the UK ambition of achieving 50 GW of installed offshore wind capacity by 2030.

However, elevated electricity prices have accelerated distributed PV deployment. Notably, projects supported by corporate power purchase agreements and wholesale power sales are anticipated to play an increasingly significant role in driving growth within the renewable energy market.

The United Kingdom endorses nuclear energy in its energy portfolio to help achieve its emissions targets, with projections indicating that nuclear power could represent 25% of electricity production by 2050. Collaborative efforts with Korea are under way to propel advances in nuclear power, spanning the development of various reactor types (including small modular reactors), decommissioning strategies, waste management solutions and supply chains.

Regarding hydrogen, the United Kingdom’s first Hydrogen Allocation Round announced 11 winning projects, set to receive GBP 2 billion (USD 2.5 billion) in OPEX support through 15-year contracts, and GBP 90 million (USD 114 million) in CAPEX funding, contingent on successful contract signing with the Low Carbon Contracts Company. The first round supports a total capacity of 125 MW, while the ongoing second round is targeting an additional 875 MW.

Furthermore, the UK government has allocated GBP 960 million (USD 1.2 billion) to the advanced manufacturing of hydrogen technologies over 2024-2028 and has updated its Low Carbon Hydrogen Standard to refine electrolytic production requirements, including definitions for eligible power purchase agreements, renewable energy guarantees of origin, and methodologies for calculating transmission and distribution losses. The updated standard now covers methane pyrolysis and outlines criteria for projects to qualify for Hydrogen Production Business Model support. The government is concurrently developing a Low Carbon Hydrogen Certification Scheme, expected by 2025.

Additionally, it has expressed support, in principle, for a hydrogen core network, following the National Infrastructure Commission's recommendations. Strategic planning for this network was published in December 2023, with a consultation envisioned for 2024. The system operator will assume responsibility for network planning by 2026.

Opportunities for growth

Aligned with the government's clean energy goals, UK renewable energy capacity is projected to increase almost 70 GW from 2024 to 2030, with utility-scale solar PV and offshore wind as the main contributors. Distributed solar PV deployment also rises in response to high electricity prices, and simplified permitting spurs onshore wind expansion, compensating for some of the offshore wind delays. Corporate power purchase agreements and merchant sales are gaining prominence as developers seek procurement options beyond traditional CfDs to capitalise on current market conditions.

For onshore wind, local permitting challenges are affecting development, especially in England. Although new government plans introduced in July 2024 aim to streamline approvals, potentially accelerating onshore growth in several years, permitting wait times and grid capacity bottlenecks remain critical obstacles across the renewable energy sector. As of mid-2024, over 180 GW of PV and 150 GW of onshore wind projects were awaiting grid connection, with significant portions at advanced stages.

For offshore wind in particular, reducing the average 10-year development time frame – half of which is spent on administrative processes – will be essential to meet long-term energy targets. Achieving the United Kingdom’s ambitious renewable energy expansion targets to meet climate goals will therefore require continued policy adjustments, infrastructure upgrades and more efficient permitting.

United States

Policy analysis

In 2021, the United States announced its intention to be carbon-neutral by 2050. It also targets 100% carbon-free electricity by 2035.

State-level renewable energy auctions (e.g. in California, New York and Illinois) and state-level renewable portfolio standards drive renewable energy deployment. The Inflation Reduction Act (IRA) is also accelerating additions, supported by clean energy tax credits and incentives. However, residential growth may slow in 2024 due to net-metering rule changes in California. Distributed solar PV growth is propelled by federal tax investment credits and state-level incentives.

The federal government aims to expand its nuclear capacity by adding 35 GW of new capacity by 2035, including plants currently under construction. By 2050, the plan is to deploy a total capacity of 200 GW, which will more than triple the country's existing nuclear capacity. Embracing nuclear energy in its energy mix, the United States intends to maintain and potentially expand its nuclear energy capacity, yet the nuclear share in the electricity generation mix will likely decrease.

As the average age of nuclear reactors in the United States is currently 41 years, the Nuclear Regulatory Commission (NRC) is reviewing applications to extend the operating lifetimes of these reactors from 60 to 80 years under the updated licence renewal programme. Additionally, the IRA has expanded clean energy tax incentives to include nuclear energy, significantly enhancing the financial viability of all active reactors. Over the past five years, 22 reactors have sought lifetime extensions. By 2024, every US reactor that had been running for at least 30 years had applied for an extra 20-year operating licence, with over 20% seeking a second 20-year extension.

Furthermore, the Advanced Reactor Demonstration Program will allocate over USD 3 billion in funding to support small modular reactors and other advanced reactor designs. The United States has already been active in developing small modular reactors. During COP28, it unveiled a variety of financial tools via its Export-Import Bank to bolster the export of small modular reactor technology.

Concerning hydrogen, the United States has committed USD 750 million to 52 projects across 24 states, with over 40% allocated to electrolyser manufacturing and 20% to fuel cell production. This funding is part of the USD 1.5 billion available under the Bipartisan Infrastructure Law for R&D and manufacturing. Additionally, the Department of Energy (DoE) allocated USD 1.9 billion to 35 clean-technology manufacturing projects under the IRA's 48C tax credit, including USD 337 million for advanced manufacturing processes to reduce costs and increase capacity, focusing on solid oxide electrolyser cells and direct CO_2 electrolysis.

The US government has also awarded USD 7 billion in grants to seven consortiums planning hydrogen hubs at an estimated total capital cost of USD 50 billion. Further CAPEX grants of USD 1.7 billion have been distributed across six projects under the Industrial Demonstration Program, with the H2Hubs initiative expected to begin operations within the next decade.

The Internal Revenue Service released proposed rules for the 45V production tax credit in December 2023, detailing requirements for lifecycle GHG emissions from hydrogen production and electricity inputs. The United States accounts for about 15% of global electrolyser investments, and a 120% increase in such investments was expected in 2024. By 2030, the country could become the third-largest exporter of hydrogen at more than 2 Mt H_2-eq/year, although delivery destinations have not yet been secured for most of it. The US government is also focused on addressing permitting challenges and advancing sensor technologies to support hydrogen infrastructure development.

Opportunities for growth

The United States is expected to add nearly 500 GW of renewable energy capacity from 2024 to 2030, primarily in solar PV and wind. The IRA remains a major catalyst, particularly for solar PV growth, although the forecasts for onshore and offshore wind have been revised downwards due to delays in the project pipeline, supply chain issues, siting and permitting challenges, and economic uncertainties. Solar PV will lead capacity additions, especially in the utility-scale segment, though residential growth is expected to slow temporarily as new net-metering rules in California, high interest rates, and tariffs on imported modules impact the market. Nonetheless, federal and state-level incentives are expected to sustain distributed solar PV growth.

Onshore wind is projected to grow more steadily in the second half of the forecast period as additional projects are approved and connected, despite ongoing siting and permitting challenges. For offshore wind, supported by federal leases and state tenders, the first major projects will become operational by 2030. However, economic challenges have led to cancellations and postponements.

Challenges impacting all segments include persistent supply chain constraints; lengthy grid connection queues; and increasingly strict siting restrictions that affect land availability, especially for solar PV and wind projects. Offshore wind deployment is impeded by the additional hindrances of project cost inflation and lengthy development timelines, limiting the immediate impact of state tenders and approvals on capacity growth within this forecast period.

Chapter 3. Levelised cost of electricity

Overview

The levelised cost of electricity (LCOE) varies widely across technologies and can be related to technological maturity; development and construction complexities and challenges; and input costs and conditions required. The LCOE of a single technology can also differ from one region to another for several reasons, including resource quality, market maturity and the cost of capital.

Solar PV and wind power are two of the lowest-cost new sources of electricity in most markets in the world today, and technological innovation and market development in this sector are projected to continue driving down costs to 2030.

Hydropower can also be a low-cost carbon-free option, though in many countries the best resources have long been developed and social acceptance and sustainability issues have become more prominent, so technology costs are not the primary determinant of its long-term outlook. Another affordable power generation choice could be bioenergy, when sustainable biomass supplies are available nearby. For other renewable energy sources such as geothermal, marine (tide and wave) and concentrated solar power, accessibility to the high-quality resources required for current technologies is limited, and costs can be high. Significant innovation is therefore needed to expand potential sites and reduce costs.

Conversely, nuclear power has been an important carbon-free energy source for more than 50 years, and technological developments are ongoing. When new projects can be delivered on time and on budget, they can be an important part of a cost-effective electricity mix, particularly in countries where renewable energy resources are more limited, of lower quality, or difficult to develop. However, several recent first-of-a-kind projects in the United States and Europe have experienced delays and cost overruns, increasing the uncertainty of the future LCOE of nuclear energy.

Introduction to LCOE

The LCOE is a metric that aggregates all direct costs associated with a technology into a single value. It represents the average cost of producing each unit of electricity over the technology's lifetime. LCOE is therefore widely used to evaluate the cost competitiveness of various power generation technologies, providing a point of comparison based on cost alone. The system value of a power plant is not captured in the LCOE but is a feature of the value-adjusted LCOE (VALCOE), as detailed in the box later in this chapter. However, neither the LCOE nor the VALCOE capture indirect costs, for instance for grid reinforcement or for emissions not priced in the market.

LCOE calculations are based on the following equation:

$$LCOE = \frac{\sum(Capital_t + O\&M_t + Fuel_t + Carbon_t + D_t) * (1+r)^{-t}}{\sum MWh * (1+r)^{-t}}$$

Where:

$Capital_t$	= total capital construction costs in year *t*
$O\&M_t$	= operation and maintenance costs in year *t*
$Fuel_t$	= fuel costs in year *t*
$Carbon_t$	= carbon costs in year *t*
D_t	= decommissioning and waste management costs in year *t*
$(1+r)^{-t}$	= the real discount rate corresponding to the cost of capital
MWh	= the amount of electricity produced annually in MWh

A technology's LCOE is thus comprised of capital costs, operation and maintenance costs, fuel costs, carbon costs and decommissioning costs. Each of these factors is crucial in defining the overall cost of producing electricity and varies significantly between different technologies and across countries.

Capital costs are typically the largest LCOE component for most power generation technologies. They are linked to financing costs and are sensitive to fluctuations in the cost of financing, which can vary depending on financial conditions, interest rates and investment risks. As markets mature and technologies advance, capital costs tend to decrease and converge, as we have seen with solar PV in the past decade.

Operation and maintenance costs are also important. They include expenses related to scheduled and unscheduled power plant upkeep. Technologies such as offshore wind turbines, which operate in harsh environments, often have higher maintenance costs than other technologies such as solar PV systems, which have fewer moving parts and require less attention. Meanwhile, fuel costs directly affect the LCOE of technologies that rely on external energy sources such as coal, natural gas, oil and biomass.

Carbon costs come into play in regions where CO_2 emissions are priced, such as the European Union (under the EU Emissions Trading System [EU ETS]) and the United States (under the Regional Greenhouse Gas Initiative [RGGI]). Power plants emitting CO_2 during combustion must pay for these emissions, raising the LCOE of fossil fuel-based technologies. Conversely, renewable energy technologies such as solar PV, wind and hydropower systems do not generate emissions during electricity production, so they are not burdened with carbon costs.

However, the LCOE measurement has significant shortcomings. It does not account for value added or indirect costs to the system, and it is particularly inadequate for comparing technologies that operate differently, e.g. variable renewables vs dispatchable technologies. For broader comparisons, it is crucial to include additional elements, such as value added to the system and integration costs (see the box below: Value-adjusted LCOE is a more robust metric of competitiveness).

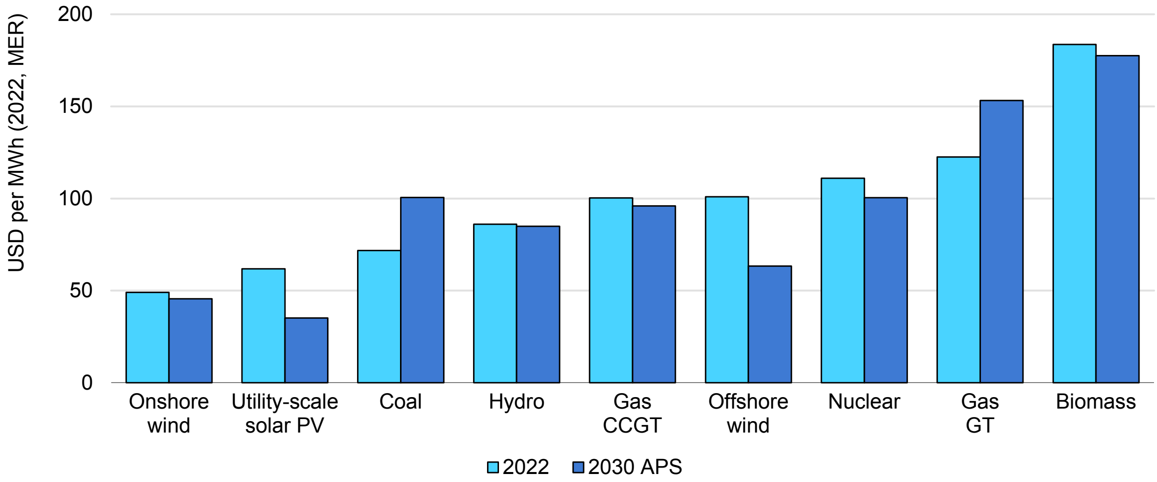
Global costs by technology

Today, solar PV and wind power are the two most affordable new electricity sources in most markets. Since 2010, the global average LCOE of utility-scale solar PV has fallen by about 90%, onshore wind by 70% and offshore wind by 60%. Hydropower, where resources are still available, also remains a relatively low-cost technology with an average LCOE of around USD 80/MWh.

In contrast, bioenergy costs vary widely depending on the cost of sustainable biomass supplies, which can become expensive if transport over any significant distance is required. In the nuclear power sector, developers have faced challenges recently, with significant construction delays and cost overruns affecting projects in the United States and Europe, leading to a LCOE of around USD 150/MWh for several projects. However, projects in China, Korea and the United Arab Emirates have been delivered on time, achieving much lower costs.

The cost trends for these technologies will continue evolving to 2030. Thanks to further technology gains and market development, solar and wind costs will continue to decline and the global average LCOE will fall to around USD 35/MWh for utility-scale solar PV; to USD 45/MWh for onshore wind; and to USD 60/MWh for offshore wind. For hydropower, which is a mature technology, average costs remain broadly stable, although individual project costs are highly dependent on site and resource availability. Nuclear power, when delivered on time and on budget, is projected to have an average LCOE of around USD 100/MWh globally, roughly the same as new and efficient natural gas-fired power plants. Bioenergy power plants have significantly higher average costs, however, as some countries, including Europe, spend more on importing sustainable biomass.

Global average LCOE of selected technologies, 2022 and 2030

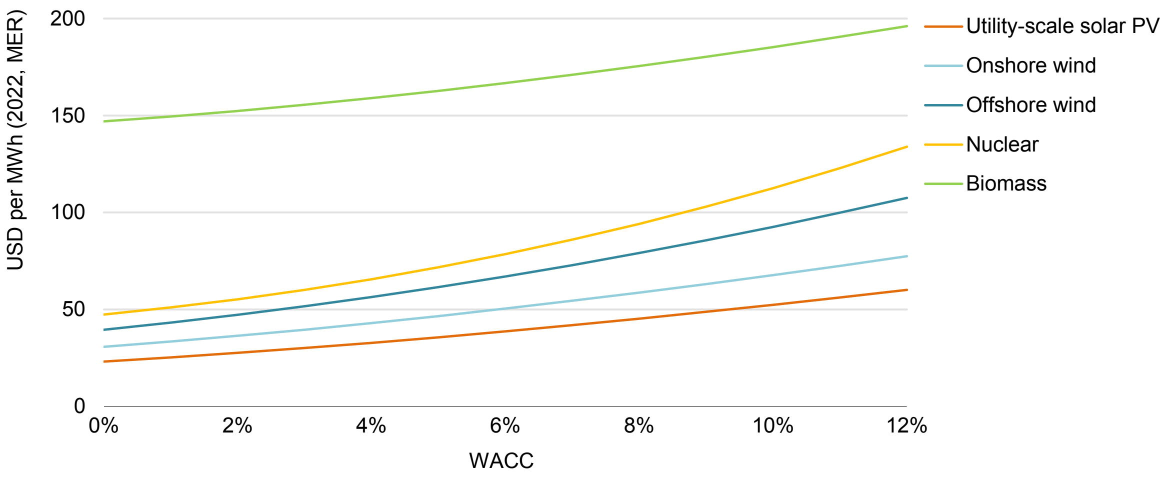


Notes: CCGT = combined-cycle gas turbine. GT = gas turbine. APS = Announced Pledges Scenario. MER = market exchange rate. Values for projection years are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario.

The weighted average cost of capital (WACC), which represents the combined average cost of procuring capital to invest in a technology, can be sourced from a variety of options, including equity and debt. Each source would have its own financing conditions and rate-of-return requirements, and they may be combined in different proportions. WACCs differ by technology for several reasons, including technology maturity, perceived risks, uncertainty of returns and technology preferences. They also vary by country depending on the market framework; governmental, institutional, policy and regulatory stability; and investor confidence. WACCs presented in this report are in real rather than nominal terms, as nominal terms would also be subject to currency-inflation uncertainty.

In advanced economies that are economically stable and have a supportive regulatory environment, the cost of capital for renewable energy projects is typically lower. This reduces the overall LCOE and makes wind and utility-scale solar PV projects more competitive. In contrast, developing countries or regions with higher economic risks may have higher costs of capital, raising the LCOE. For example, the LCOE for utility-scale solar PV in Germany is nearly half that of South Africa, despite South Africa's more favourable geographic position for solar PV electricity generation.

Effect of WACC changes on the LCOE of selected technologies, 2030



Notes: WACC = weighted average cost of capital. LCOE = levelised cost of electricity. MER = market exchange rate. Values for projection years are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario.

WACC is a crucial factor in determining a technology's overall LCOE, and capital-intensive technologies are generally more sensitive to WACC changes. For instance, solar PV, wind, hydropower and nuclear power are highly capital-intensive, and their LCOE can fluctuate by 20% or more with just a 3% change in WACC. Bioenergy, in contrast, is less affected by WACC as its fuel costs play a more significant role in determining its LCOE, especially compared with other renewables that incur no fuel costs. The table below presents IEA modelling assumptions for WACCs across selected countries and technologies.

Weighted average cost of capital assumptions by region and technology

	Nuclear	Coal	Gas CCGT	Utility-scale solar PV	Onshore wind	Offshore wind
Argentina	8%	8%	8%	6%	6%	6%
Brazil	8%	8%	8%	6%	6%	6%
Canada	9%	9%	9%	4%	4%	5%
China	8%	8%	8%	5%	5%	5%
India	8%	8%	8%	7%	7%	8%
Indonesia	8%	8%	8%	6%	6%	6%
Japan	9%	9%	9%	4%	4%	5%
Korea	9%	9%	9%	4%	4%	5%
Mexico	9%	9%	9%	4%	4%	5%
Russia	8%	8%	8%	6%	6%	6%
South Africa	8%	8%	8%	6%	6%	6%
United Kingdom	9%	9%	9%	4%	4%	5%
United States	9%	9%	9%	5%	5%	6%

Note: WACC values are in real, pre-tax terms.

Solar PV and wind

Wind and solar PV technologies have evolved from niche into mainstream carbon-free energy sources, thanks largely to a virtuous cycle of policy support and technology cost reductions. Their modularity, especially of solar PV, allows for wide deployment in diverse geographical and economic contexts. However, despite their widespread availability and adaptability, wind and solar PV LCOE vary significantly by country. This disparity results primarily from variations in capacity factors and the cost of capital, which together determine the economic viability and competitiveness of renewable energy projects.

The economies of scale enabled by the modularity of wind and solar PV technologies have facilitated technological advances and cost reductions. As more units are produced and installed, manufacturing, installation and maintenance costs continue to decline. This has made wind and solar PV increasingly competitive with conventional energy sources, even in markets where fossil fuels have traditionally dominated.

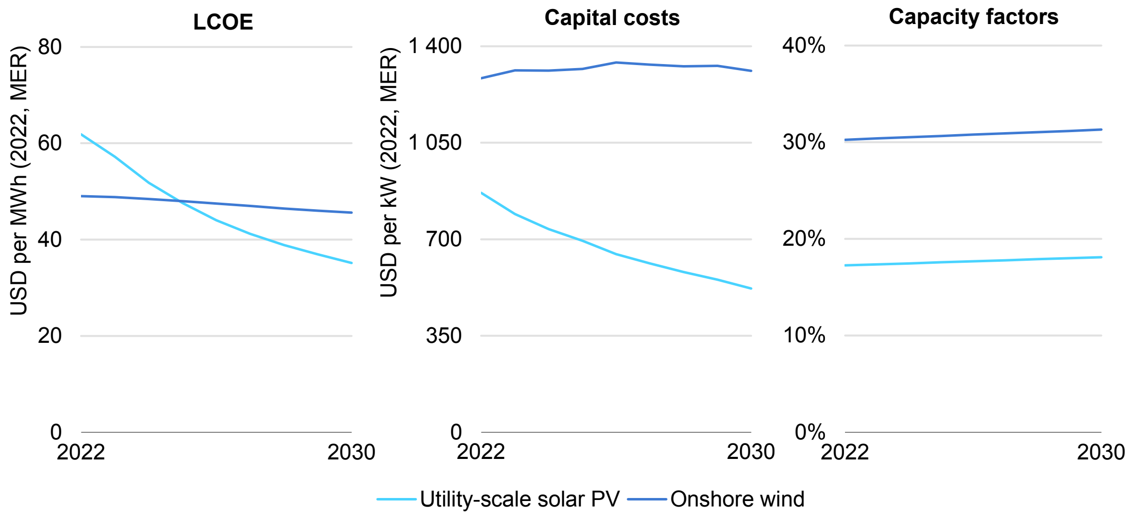
Nevertheless, the overnight capital costs of solar PV and onshore wind reflect far more than the physical technology and its relative modularity. Overnight costs also encompass a range of direct, indirect and owner costs. Direct costs include expenditures for essential components such as site preparation, civil works, materials, equipment and construction labour. Indirect costs cover design, engineering, supervision, on-site administrative expenses and any necessary backup facilities. Additionally, owner costs may involve general administration before and during construction, plant-specific R&D, site selection, acquisition and licensing.

Crucially, a financial contingency plan to address potential risks and cost overruns must also be factored into overnight costs. By encompassing all these elements, overnight costs provide a complete picture of the financial investments required and demonstrate country differences beyond globalised technology acquisition. Two challenges that can raise a project's cost significantly are stringent permitting requirements and land-access constraints.

Another key factor influencing solar PV and wind LCOE is performance, one measure of which is the capacity factor (i.e. average output over the year divided by maximum output capacity). For wind energy, capacity factors are affected by wind speed and consistency, which can vary dramatically by location. Coastal and high-altitude areas often experience more consistent and stronger winds, leading to higher capacity factors and, consequently, a lower LCOE. In contrast, inland or less-windy areas may have lower capacity factors, resulting in a higher LCOE.

Similarly, the capacity factors of solar PV systems are determined by solar irradiance, which varies based on geographical location, weather patterns and seasonal changes. Regions with high solar exposure tend to have higher capacity factors, making solar PV projects more economically attractive. Conversely, solar PV systems in areas with frequent cloud cover or lower solar irradiance may have a higher LCOE.

Global average LCOEs, capital costs and capacity factors of utility-scale solar PV and onshore wind installations, 2022-2030

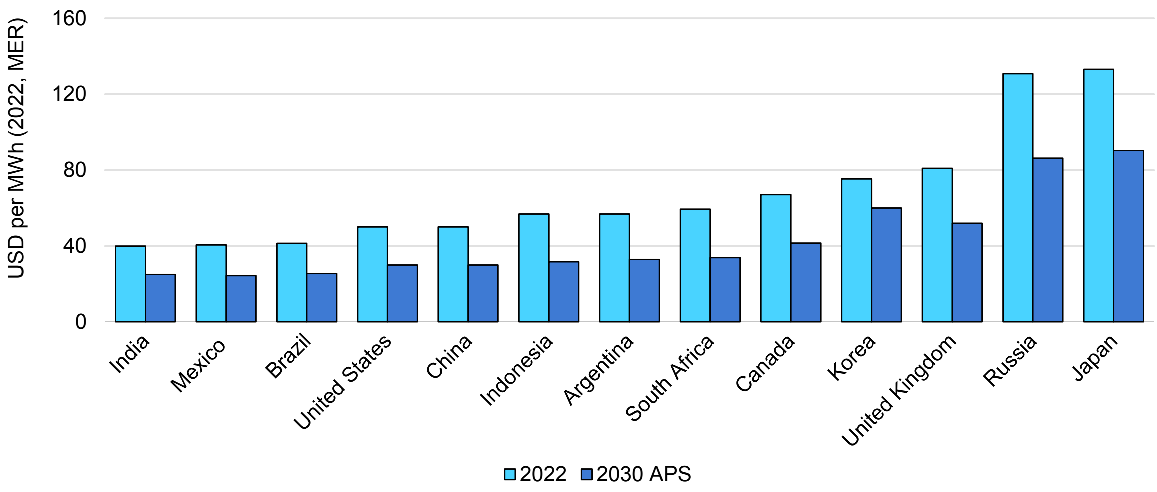


Notes: LCOE = levelised cost of electricity. MER = market exchange rate. Values for projection years are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario. Utility-scale solar PV includes ground-mounted projects, generally with capacities over 10 MW.

LCOEs for both utility-scale solar PV and onshore wind are projected to decline by 2030, albeit more significantly for utility-scale solar PV. A decrease in capital costs, which remain the largest component of LCOE for these technologies, is the primary reason for this decline. Capital costs are expected to drop largely because of falling manufacturing and construction expenses. At the same time, performance is expected to continue improving, leading to higher capacity factors for both solar and wind systems. As a result, by 2030 the global average LCOE for utility-scale solar PV will be 40% lower than in 2022, while for onshore wind it will be around 10% lower.

The LCOEs of these technologies vary significantly across countries due to differences in resource quality, market maturity and the cost of capital. By 2030, LCOEs for utility-scale solar PV are expected to be lowest in countries like India, Mexico and Brazil, where solar resources are abundant, with costs of around USDS 25/MWh. These nations benefit from high-quality sunlight and optimal locations for solar PV installations. Conversely, in countries such as Japan, where space for solar installations is limited, and Russia, where solar resources are harder to access, LCOEs for utility-scale solar PV are more than three times higher, reaching around USD 90/MWh.

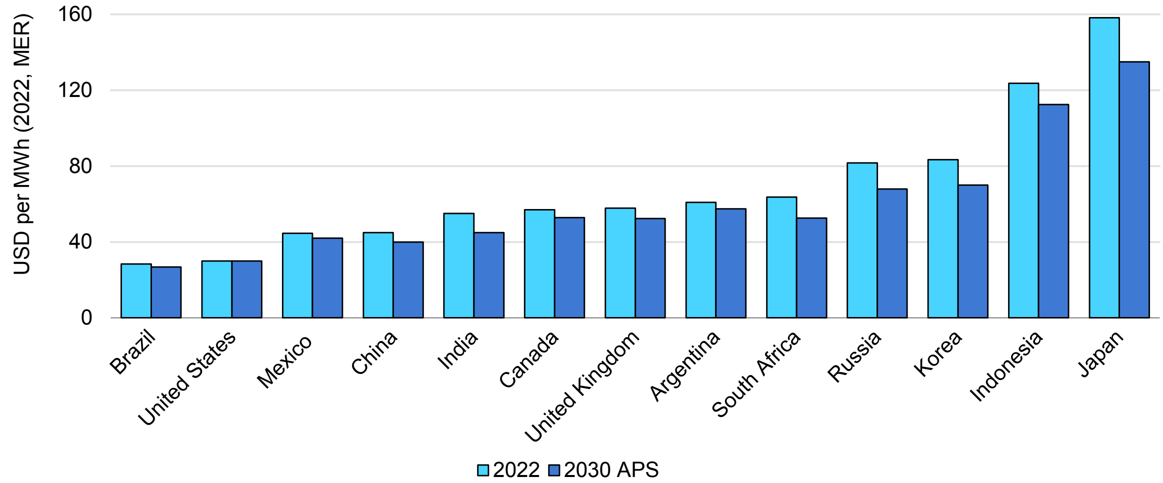
LCOEs of utility-scale solar PV for selected G20 countries, 2022 and 2030



Notes: LCOE = levelised cost of electricity. MER = market exchange rate. APS = Announced Pledges Scenario. Values for projection years are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario. Utility-scale solar PV includes ground-mounted projects, generally with capacities over 10 MW.

Similarly, for onshore wind, countries that have abundant wind resources and can access lower costs of capital tend to have the lowest LCOE, for instance Brazil and the United States. In contrast, it will be difficult to reduce the LCOE in nations such as Japan because of rising space limitations and high land costs for onshore wind installations, and in Indonesia due to high investment and financing costs.

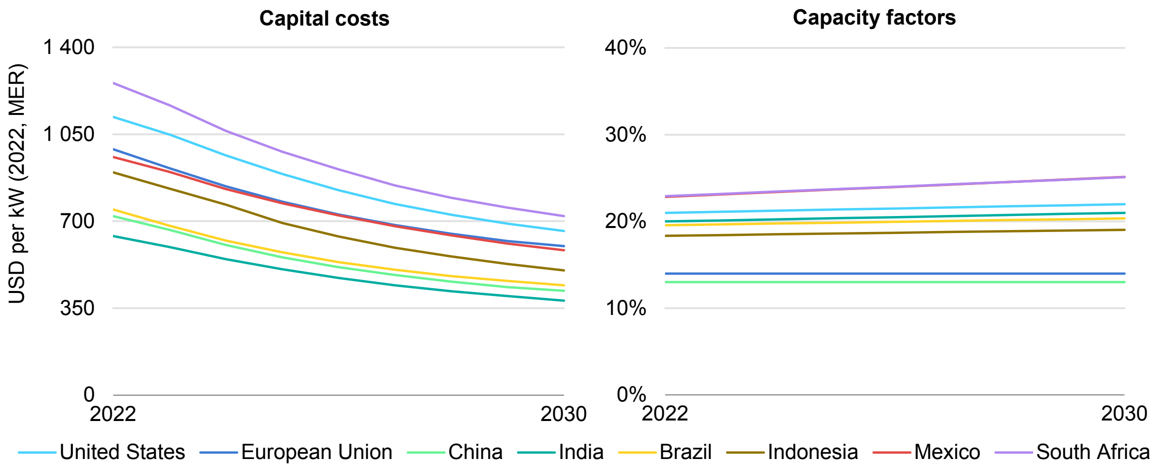
LCOEs of onshore wind for selected countries, 2022 and 2030



Notes: LCOE = levelised cost of electricity. MER = market exchange rate. APS = Announced Pledges Scenario. Values for projection years are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario.

For utility-scale solar PV, for which costs have already fallen 90% since 2010, capital costs continue to decline across selected regions, with an average decrease of 40% expected by 2030. These costs are lowest in countries such as India and China, while in places such as Indonesia, where capital costs are currently the highest of the selected nations, they are also projected to decrease 40% compared with 2022. As solar PV technology matures, performance improves, leading to higher capacity factors across all regions. In some countries, for example Mexico and South Africa, average utility-scale solar PV capacity factors are expected to reach or exceed 25%.

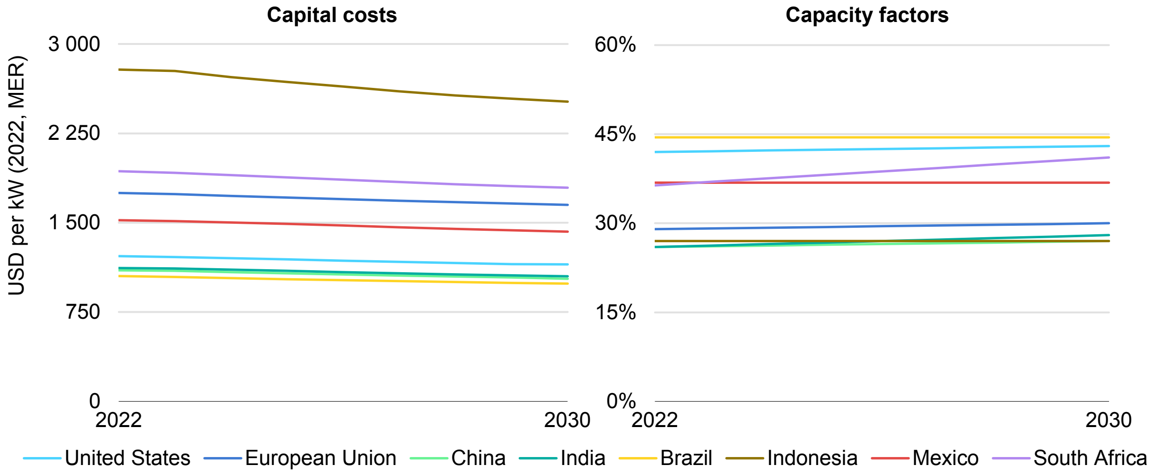
Utility-scale solar PV capital costs and capacity factors for selected regions, 2022-2030



Notes: MER = market exchange rate. Values for projection years are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario.

Although capital costs for onshore wind do not fall as significantly as for utility-scale solar PV, they are expected to decrease 10% on average by 2030 and continue to be lowest in countries like India, China and Brazil. While capacity-factor increases to 2030 for onshore wind are more modest than for solar PV, they are higher on average than solar PV capacity factors today, helping drive down the onshore wind LCOE. Despite their more modest increase, onshore wind capacity factors play an important role in reducing the overall LCOE of wind technology, with some countries such as Brazil, the United States, South Africa and Mexico reaching around 40% or greater.

Onshore wind capital costs and capacity factors for selected regions, 2022-2030



Notes: MER = market exchange rate. Values for projection years are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario.

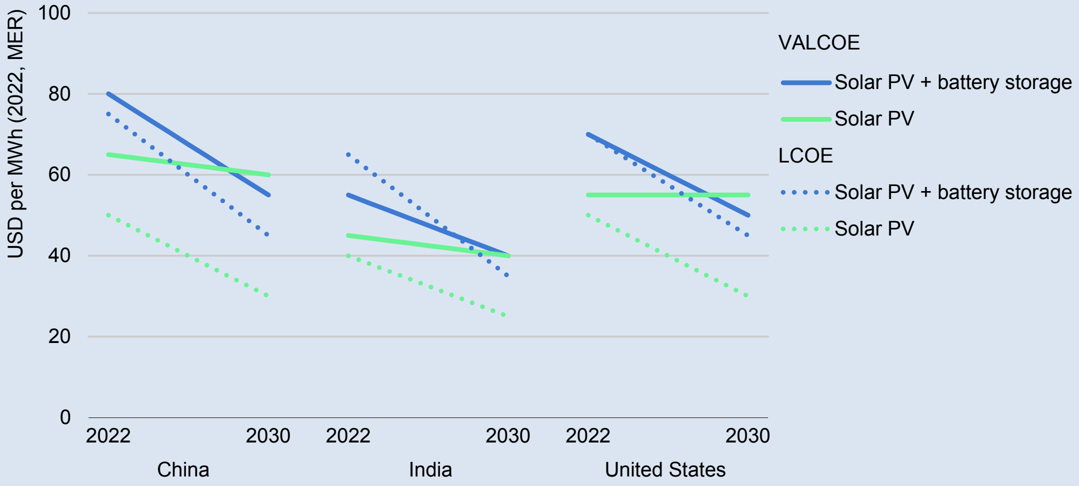
Value-adjusted LCOE is a more robust metric of competitiveness

The levelised cost of electricity (LCOE) is a commonly used metric that encompasses all costs directly associated with a given technology – including construction, financing, fuel and maintenance costs. However, while the LCOE can reveal which technology has the lowest average cost, it takes no account of impacts on and interactions with the overall power system and does not necessarily indicate the least-cost option for the system.

In light of this, the IEA developed and employs a value-adjusted LCOE (VALCOE), a more complete measure of competitiveness that combines technology costs (the LCOE) with the value of three system services the technology provides – energy, flexibility and capacity – by drawing on detailed hourly modelling of electricity demand and supply.

Power systems have differing needs depending on generation mix, demand patterns and renewable energy penetration. As solar PV and wind shares continue to rise, the value of energy provided by these sources tends to decrease compared with the system average, and the value of flexibility tends to increase. Both trends underscore the importance of looking beyond the LCOE to determine competitiveness.

VALCOEs and LCOEs of solar PV and solar PV-plus-battery storage



Notes: LCOE = levelised cost of electricity. VALCOE = value-adjusted levelised cost of electricity. MER = market exchange rate. Values for projection years are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario.

The VALCOE can also indicate the competitiveness of energy storage, either as a stand-alone option or paired with other energy sources. For example, for China, India and the United States, solar PV paired with battery storage becomes quite competitive with solar PV-only when VALCOE values are considered rather than just LCOE. This reflects the increasing importance of generating energy at the right time and providing flexibility and capacity services to the grid. However, based on the LCOE alone, solar PV without storage appears to be the lower-cost option. Pairing solar PV and battery storage is already one of most competitive options, as installed costs for both have fallen 90% over the past decade.

The VALCOE is part of a broader family of metrics that extend beyond the LCOE, including the system LCOE and traditional measurements of profitability and cost-benefit analysis. However, although the VALCOE provides a broader metric of competitiveness than the LCOE, it does not include the cost of power generation emissions that are not priced in the market, nor does it cover grid-related costs, as they are highly site-specific and affected by the power generation mix.

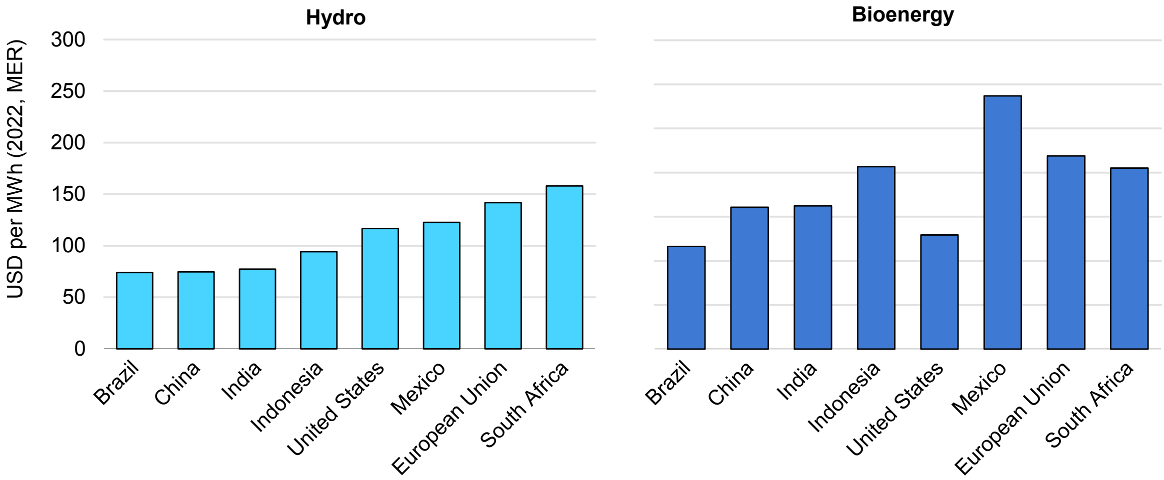
Grid-related costs, which make up 10-30% of total power system costs in major economies today, tend to rise as solar PV and wind shares increase, but this relationship is non-linear, with costs climbing more quickly at higher variable renewable energy shares. Additional grid costs include investments in distribution grids and in transmission – for extensions to connect new wind and solar PV projects, which tend to be further from existing grids (particularly offshore wind parks), and for grid reinforcement or upgrades. Neither the LCOE nor the VALCOE capture additional grid-related costs, as only comprehensive system cost assessments can account for them properly.

Hydropower and bioenergy

Hydropower and bioenergy are the carbon-free energy sources with the longest histories in the power sector. Hydropower has been the foremost low-emissions source of electricity for the past 50 years, producing 18% of global electricity supplies during this period. In many regions, most of the technical potential for hydropower has been developed, limiting further expansion to countries in Africa, Latin America and Southeast Asia.

Bioenergy has played a smaller role in the power sector, surpassing 1% of global electricity generation for the first time in 2004. Prospects for expanding modern bioenergy use are limited by the availability and price of fuels, which may need to be imported and are subject to sustainability requirements in some countries.

LCOEs of hydropower and bioenergy for selected regions, 2030



Notes: LCOE = levelised cost of electricity. MER = market exchange rate. Values for projection years are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario.

While the LCOEs of hydropower and bioenergy vary among the selected countries, bioenergy has a higher LCOE than hydropower through 2030 in all of them. This primarily reflects bioenergy fuel costs, which fluctuate significantly between countries and can also vary by season (whereas hydro, like solar PV and wind, does not have any fuel costs). Despite hydropower's higher average capital costs and lower average capacity factors, the hydropower LCOE remains lower than bioenergy's to 2030.

Among the selected countries, hydropower LCOE is lowest in Brazil, China and India. These countries benefit from well-below-average capital costs and more favourable geographic and hydrological conditions than other regions. In addition, they have gained valuable experience with several large-scale projects in recent years – with China alone adding 165 GW over the past decade and Brazil and India together adding another 35 GW – reducing the risk of cost overruns and project completion delays.

For bioenergy, Brazil has the lowest LCOE, followed by the United States, owing to the availability of low-cost domestic biomass supplies. When biomass supplies are more expensive or less abundant, the LCOE of bioenergy can rise significantly. Variations in capital costs are less pronounced for bioenergy, as it is a mature technology.

Nuclear power

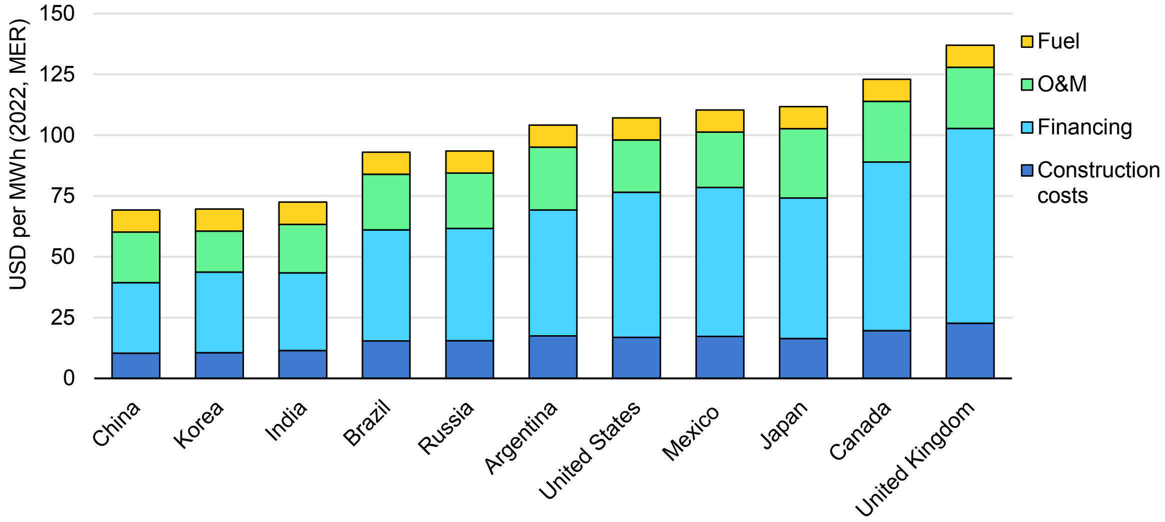
Nuclear power has been an important carbon-free energy source for more than 50 years, helping the world avoid about 1.5 Gt of CO_2 emissions each year. Although nuclear power technology development continues apace, several recent first-of-a-kind projects in the United States and Europe have suffered delays and significant cost overruns. Many of these first-of-a-kind projects, if delivered at current costs, would have an LCOE ranging from USD 150/MWh to over USD 200/MWh. Delay and cost-overrun risks vary by region, however, with a number of recent nuclear power projects being completed very close to original timelines and budgets in Korea, China and the United Arab Emirates, each with an LCOE well below USD 100/MWh.

Looking forward to 2030, for new large-scale projects delivered on time and on budget, most LCOEs for nuclear plants would be around USD 100/MWh, with the lowest at roughly USD 70/MWh in China, Korea and India. At these levels, nuclear can be part of a cost-effective electricity mix even in countries where renewable energy resources are more limited, of lower quality, or difficult to develop.

Construction costs are the clear differentiator between high- and low-cost nuclear power, with many projects in advanced economies costing twice as much or more as those in the lowest-cost markets. Construction costs vary depending on a number of factors, including reactor design, site location, skill availability and experience. In contrast, fuel costs and operation and maintenance costs are much more consistent across the selected countries.

In addition to conventional large reactors, small modular reactors are also under development. In Russia and China the first projects are already online, and in advanced economies they are anticipated for around 2030. Partly because a wide range of designs is being pursued, there is significant uncertainty about delivered costs.

Projected LCOE of nuclear power for selected regions, 2030



Notes: LCOE = levelised cost of electricity. MER = market exchange rate. O&M = operation and maintenance. Values for projection years are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario. Nuclear costs are based on established technologies for projects delivered in 2030.

Classifying carbon-free technology costs

Carbon-free options available for each country can be classified as low-, medium- or high-cost based on the technology's LCOE and resource potential. Considering the important differences between variable and dispatchable resources, the table below provides separate LCOE evaluations for the two categories. While "variable renewables" refers to utility-scale solar PV, onshore wind and offshore wind, "dispatchable carbon-free" covers nuclear and hydropower. The deployment of all technologies in each classification category is assumed, and when resource potential is very limited, costs are indicated as high.

The medium-cost range for dispatchable technologies is based on historical average power generation costs – which have been mostly in the range of USD 70-110/MWh. LCOEs above this range are categorised as high-cost, as they tend to raise average system costs, while LCOEs below this range are deemed low-cost and help reduce the average. While most G20 countries have access to low- or medium-cost dispatchable carbon-free electricity sources, we have identified eight countries where costs for these technologies are high or resources are constrained.

As variable renewable energy sources tend to provide less value to power systems than dispatchable technologies do (see box above on value-adjusted LCOE), their medium-cost range is USD 60-100/MWh. Variable renewables within this cost range would generally have only minor effects on the system's average power generation costs, whereas costs above this range would tend to raise power generation costs, and those below would pull down average costs. Variable renewables are classified as low- or medium-cost in all G20 countries, underscoring their affordability and widespread availability.

Overview of LCOE of carbon-free sources in G20 countries

	Variable renewables	Dispatchable carbon-free
Argentina	Low	Low
Canada	Low	Low
China	Low	Low
India	Low	Medium
Brazil	Low	Medium
Indonesia	Low	Medium
United States	Low	Medium
Mexico	Low	High
Australia	Low	High
Saudi Arabia	Low	High
South Africa	Low	High
Korea	Medium	Low
Russia	Medium	Medium
Türkiye	Medium	Medium
France	Medium	Medium
Japan	Medium	High
United Kingdom	Medium	High
Italy	Medium	High
Germany	Medium	High

LCOE
USD per MWh (2022, MER)   Low Medium High

Notes: MER = market exchange rate. Values for projection years are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario. The medium range for variable renewables is USD 60-100/MWh (at the 2022, MER), and for dispatchable carbon-free sources it is USD 70-110/MWh (at the 2022, MER). Average costs are based on projected LCOE and deployment by technology for 2023-2030.

Chapter 4. G20 country clusters

Introduction to screening criteria

To expand learning opportunities for governments and stakeholders, we have grouped G20 countries into clusters according to their similarities. While no clustering exercise is perfect and differences among countries within the same cluster are inevitable, this approach aims to identify groups of countries facing similar growth challenges and opportunities to facilitate the formulation of general policy recommendations. Groupings are based on screening criteria, including GDP per capita; solar PV and wind shares in the generation mix; installed capacity shares of dispatchable carbon-free energy sources; cross-border interconnection capacity relative to demand; population density (reflecting land availability); and LCOE (described extensively in Chapter 3).

Clustering criteria and ranges

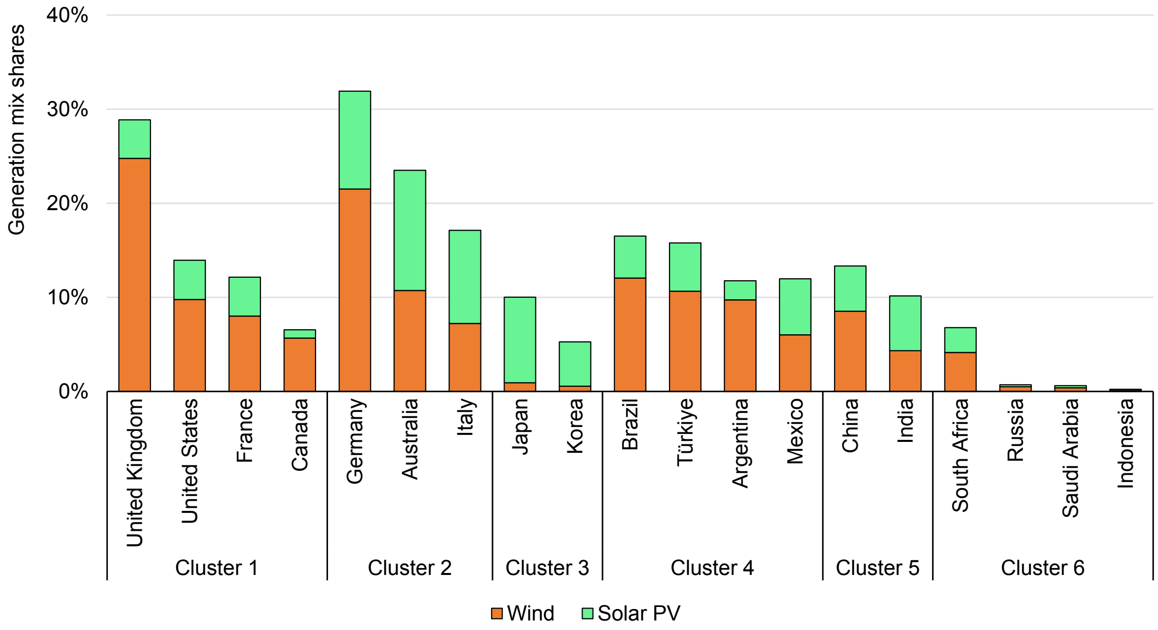
Variable carbon-free generation share	>15%	≥5% to ≤15%	<5%
Dispatchable carbon-free installed capacity share	>25%	≥15% to ≤25%	<15%
Interconnection capacity relative to electricity demand	>5%	≥1% to ≤5%	<1%
GDP per capita (USD)	>20 000	≥10 000 to ≤20 000	<10 000
Population density (ppl/km^2)	<35	≥35 to ≤150	>150

Variable carbon-free generation share

In the context of energy transitions, national renewable energy targets and the fulfilment of country climate ambitions, it is highly relevant to use the share of variable carbon-free energy in the generation mix as a criterion.

In most countries, the most prominent variable carbon-free technologies are wind and solar PV, and their variability presents both advantages and challenges for energy security, grid management and electricity costs. Countries that effectively integrate high shares of variable carbon-free energy sources into their power systems tend to have developed advanced grid management strategies and market mechanisms to manage the non-dispatchability of these sources.

Solar PV and wind in the generation mix in G20 countries, 2022

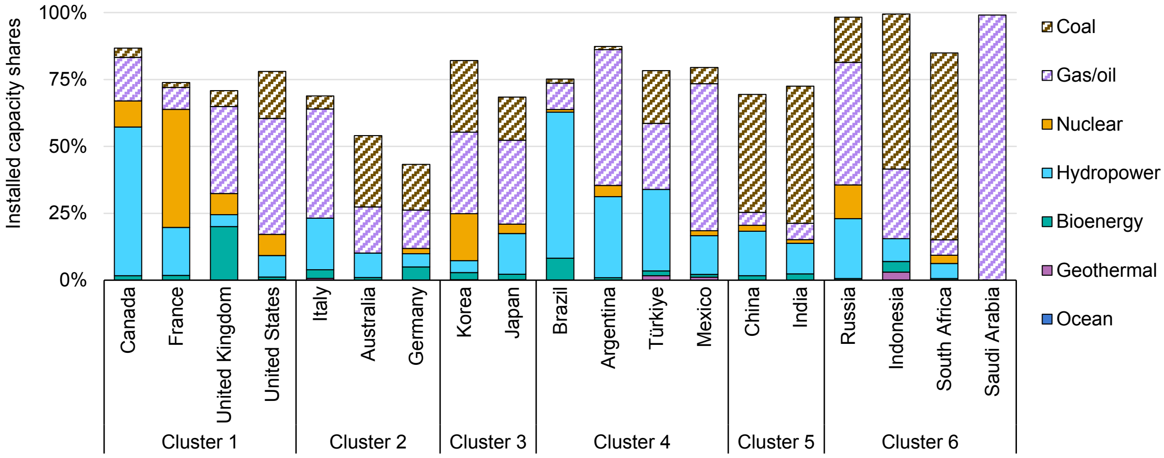


IEA. CC BY 4.0.

Dispatchable carbon-free installed capacity share

To understand the opportunities and challenges countries face on their energy transition pathways, it is crucial to include dispatchable carbon-free installed capacity shares (particularly hydropower and nuclear) as a clustering criterion. Hydropower, the largest source of renewable electricity globally, and nuclear power, a significant carbon-free energy source, are both pivotal in reducing greenhouse gas emissions and supplying dispatchable carbon-free electricity.

Dispatchable installed capacity in G20 countries, 2022



Note: Coal and gas/oil are considered non-carbon-free energy sources, whereas ocean, geothermal, bioenergy, hydropower and nuclear are all considered carbon-free energy sources.
Sources: IEA analysis based on IEA (2024), Renewable Energy Progress Tracker (accessed 26 January 2025) and Global Energy Monitor (2024), Global Integrated Power Tracker (accessed 26 January 2025).

Hydropower, with its ability to provide large-scale electricity generation and grid stability, is essential for balancing variable carbon-free energy sources such as wind and solar. While nuclear power is generally less adaptable than hydropower because of its lengthy ramp-up and ramp-down times, it is crucial for grid resilience in countries such as France. Economies with significant shares of hydropower and nuclear in their installed capacity are often leaders in maintaining low carbon intensity in their electricity generation.

Per-capita GDP influences carbon-free electricity deployment

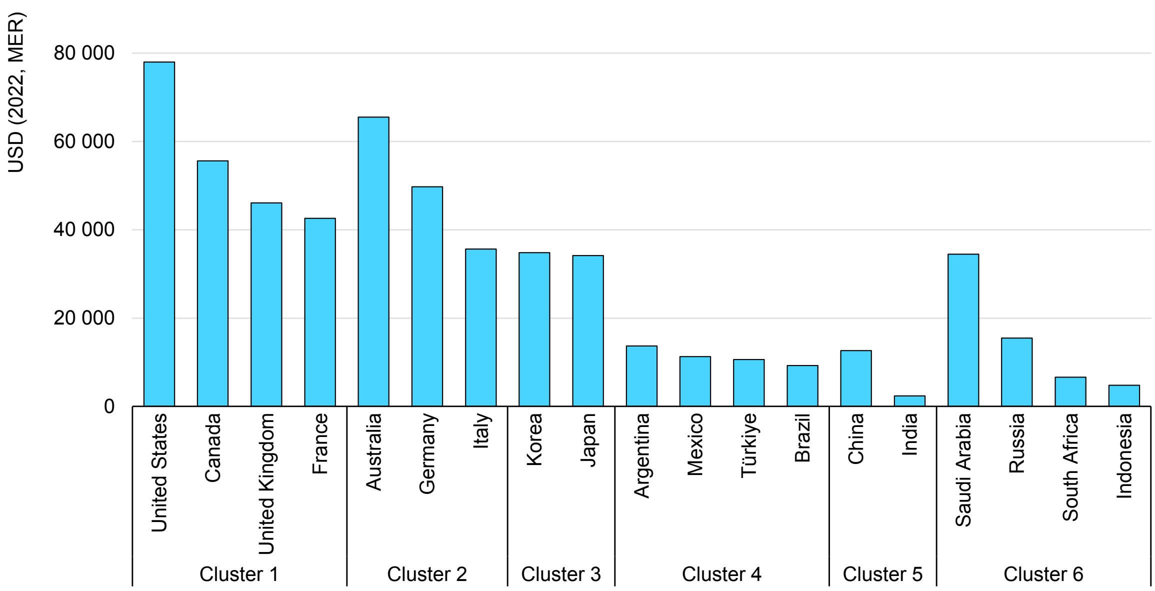
Disparities between advanced and emerging economies in adopting carbon-free technologies are considerable. These differences are rooted in the complex interplay of financial institutions, policy frameworks and existing infrastructure.

Advanced economies generally have greater financial resources and more developed financial markets, which allows them to invest heavily in carbon-free technology research, development and deployment. In contrast, access to capital is more restricted in emerging economies and borrowing costs are higher. Advanced economies also benefit from more disposable income for government support of carbon-free technologies, while emerging economies often have to contend with budget constraints and competing priorities, such as poverty alleviation and other infrastructure developments.

The policy landscape is a crucial determinant of carbon-free energy uptake. Advanced economies typically have more ambitious renewable energy and net zero emission targets, and their policies are usually backed by substantial government incentives, subsidies and tax breaks designed to stimulate the adoption of carbon-free technologies. Similarly, among G20 countries, advanced economies have more stringent carbon pricing mechanisms.

In advanced economies, grid investments have increased steadily in the past decade, supporting the integration of renewable energy sources such as solar PV and offshore wind. However, these grids still suffer from bottlenecks. In contrast, emerging economies, excluding China, have experienced declining grid investments even though electricity demand and energy access needs are increasing. The primary barriers to grid development vary by region.

Gross domestic product per capita in G20 countries, 2022



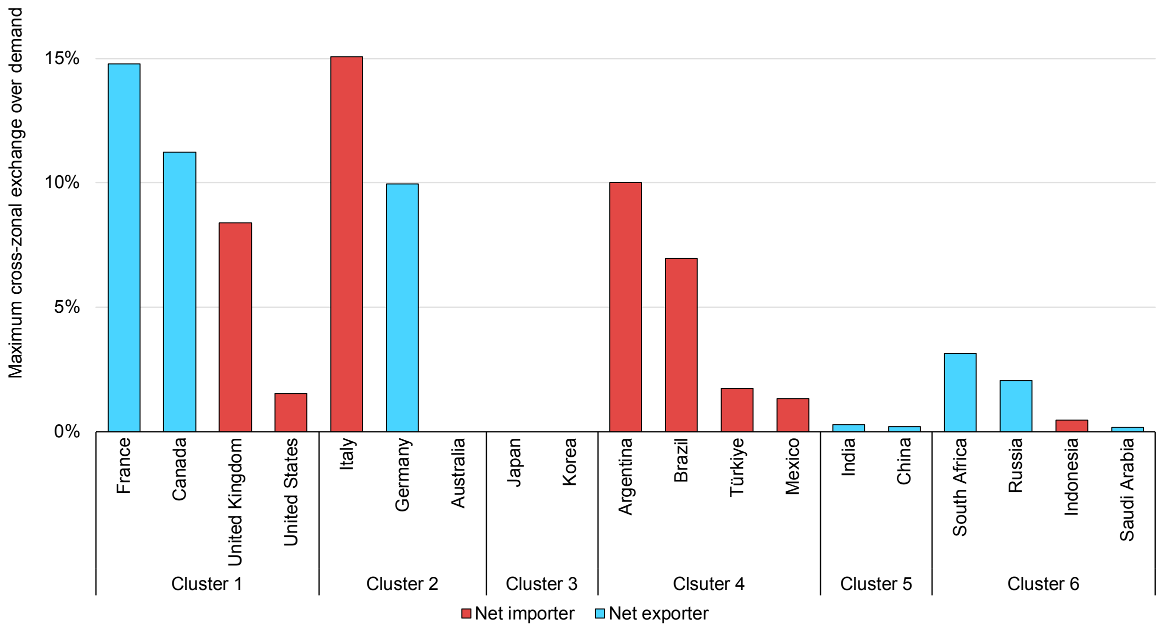
Notes: MER = market exchange rate. Values for GDP per capita reflect 2024 prices, translated into US dollars in 2022.
Source: IEA analysis based on IMF (2024), World Economic Outlook (accessed 26 January 2025).

Cross-border interconnections

Another important criterion is cross-border interconnections, as they enhance energy system flexibility and resilience, allowing for the integration of variable carbon-free energy sources such as wind and solar power. By fostering competition and reducing overall costs, interconnections support the development of a more integrated and efficient electricity market.

By enabling the sharing of resources and infrastructure, countries can optimise the use of their carbon-free energy potential and improve grid stability. This is particularly critical as the share of variable renewables continues to grow, necessitating advanced co-ordination and co-operation.

Maximum annual cross-border exchanges relative to electricity demand in G20 countries, 2019-2022



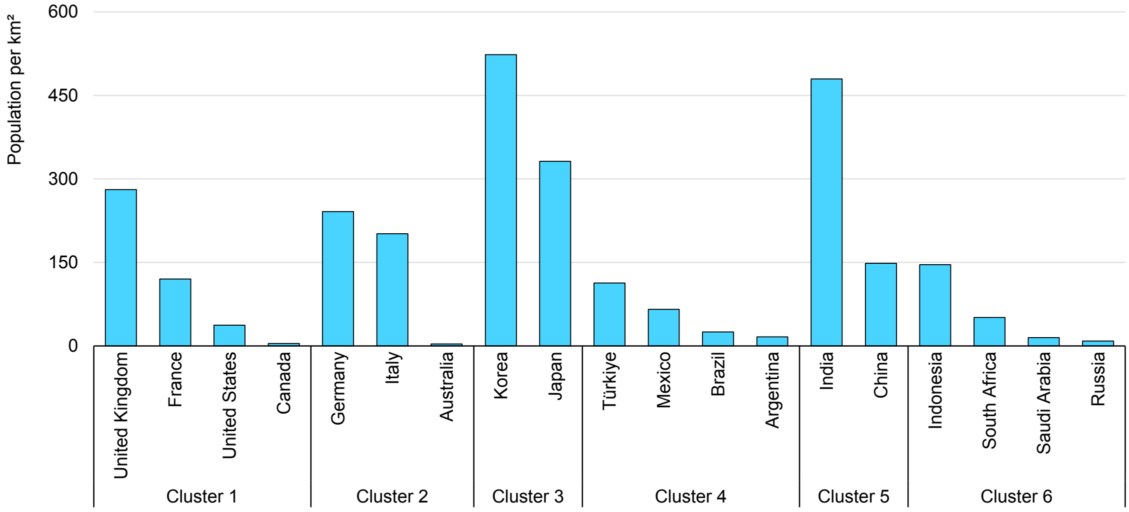
Note: Values for annual maximum cross-border exchanges for 2019-2022 divided by electricity demand include power plant self-consumption.

Population density

Population density is another criterion for country clustering, as it significantly impacts land availability for utility-scale solar PV and wind projects. In sparsely populated regions, large-scale renewable energy installations can facilitate rapid solar and wind capacity expansion. Conversely, land scarcity is more likely in high-population-density areas, making it more challenging to deploy renewable energy projects extensively without competition from other land uses.

Furthermore, population density is closely linked with social acceptance issues. In densely populated areas, developing renewable energy projects close to residential zones can provoke strong public opposition due to concerns over land use, visual impact and noise. Clustering countries based on population density thus provides insights into potential barriers and opportunities for expanding renewable energy infrastructure, highlighting the need for strategies tailored to both land availability and social dynamics.

Population density in G20 countries, 2022



Source: IEA analysis based on United Nations (2024), 2024 Revision of World Population Prospects (accessed 26 January 2025).

Carbon-free technology costs

As described in the previous chapter, the carbon-free options available for each country can be classified as low-, medium- or high-cost based on analysis of the levelised cost of electricity (LCOE) and resource potential of each technology. Considering the important differences between variable and dispatchable resources, the figure below illustrates separate evaluations for the two categories. “Variable renewables” in this case refers to utility-scale solar PV, onshore wind and offshore wind, while “dispatchable carbon-free” costs are for nuclear and hydropower.

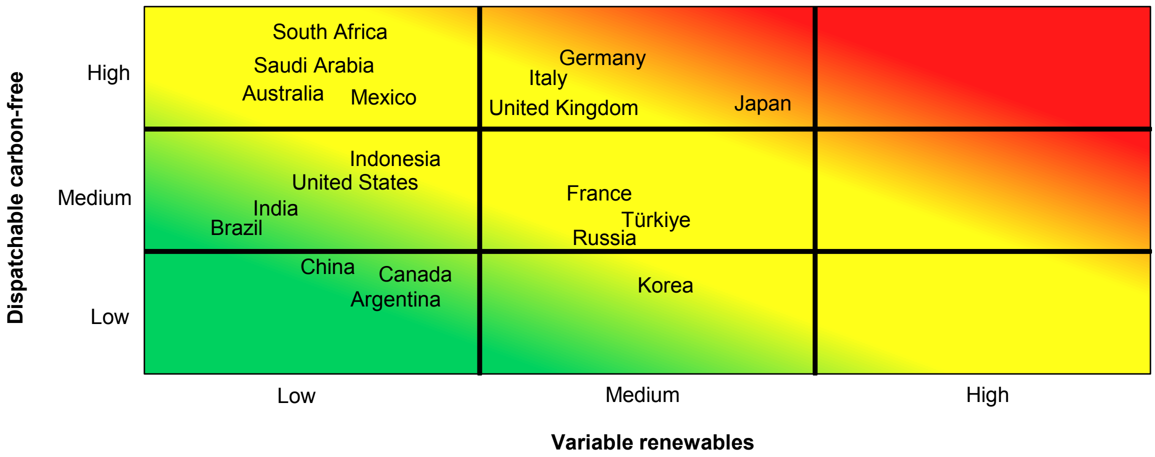
All regions employ either low- or medium-cost variable renewables thanks to low technology costs and widespread resource availability. While regions differ in their preferences for solar PV or wind, the past decade’s reductions in installed costs have helped ensure that at least one variable renewable option is available and affordable in many regions.

As power systems decarbonise, energy transition security will depend critically on the affordability and availability of dispatchable carbon-free technologies, as they provide additional value to power systems. For low-cost dispatchables, Argentina and Canada benefit mainly from hydropower complemented by nuclear; China relies on both technologies equally; and Korea focuses mainly on nuclear.

Medium-cost dispatchables are employed in a wide range of countries such as the United States and France, which use both hydropower and nuclear widely, while Brazil focuses more on its abundant hydropower resources. However, hydropower expansion is not possible in some countries and, for several, nuclear costs have remained high in recent years – although they could fall in the future.

No G20 country has a high-cost classification for both variable renewables and dispatchable carbon-free energy sources, and some have multiple low-cost options in both categories. This indicates that carbon-free energy resources are available, and that technology choices are location-dependent.

LCOE classifications of carbon-free technologies in G20 countries



Notes: LCOE = levelised cost of electricity. Values for projection years are based on IEA modelling in World Energy Outlook 2023, Announced Pledges Scenario. The medium range for variable renewables is USD 60-100/MWh (at the 2022 market exchange rate [MER]) and USD 70-110/MWh (at the 2022, MER) for dispatchable carbon-free sources. Average costs were calculated based on projected LCOE and deployment by technology from 2023 to 2030.

Country groups by screening criteria

Cluster 1: High shares of dispatchable carbon-free energy

Cluster characteristics

Cluster 1, comprising Canada, France, the United Kingdom and the United States, demonstrates a significant solar PV and wind presence in the electricity generation mix.

Canada's share of variable carbon-free energy sources is low compared with the other countries, even though it has vast potential to integrate higher levels owing to its significant hydropower capacity, which currently makes up almost 60% of total installed capacity. Similarly, nuclear energy and hydropower account for more than 60% of France's installed capacity.

This cluster is thus characterised by a high share of dispatchable carbon-free installed capacity, enhancing the system flexibility needed to integrate renewable energy, particularly solar PV and wind. An essential feature of this cluster is its high level of interlinkages, which facilitates energy trading and enhances stability. Notably, the United States' vast area, with its inherent dispersal of energy sources and demand centres, compensates for the country's relatively low level of interconnectedness.

Population density varies within the cluster, but the United Kingdom stands out for its high deployment of variable carbon-free technologies despite its considerable number of people. Notably, nearly half of the country's installed wind power capacity comes from offshore wind, which is unaffected by population density.

Carbon pricing mechanisms are prevalent across this cluster, albeit with varying degrees of coverage. European countries exhibit moderate coverage, whereas Canada demonstrates a high level of implementation. The United States, however, displays low coverage relative to its counterparts.

Screening criteria for countries in cluster 1

Cluster 1	Canada	France	United Kingdom	United States
Variable carbon-free generation share	🟡	🟡	🟢	🟡
Dispatchable carbon-free capacity share	🟢	🟢	🟢	🟡
Interconnections	🟢	🟢	🟢	🟡
GDP per capita	🟢	🟢	🟢	🟢
Population density	🟢	🟡	🔴	🟢

Note: Dot colours correspond to the ranges defined in the screening criteria section above.

Common obstacles within the cluster

A major impediment to expanding carbon-free energy source uptake is inadequate grid capacity and flexibility. Both the United States and Canada identify grid infrastructure as a critical challenge. Upgrading and expanding the grid is thus essential to accommodate the variability of variable renewable energy and maintain system stability.

Prolonged permitting processes are also significantly delaying the deployment of carbon-free energy projects. UK permitting wait times are very long, slowing the progress of both wind and solar projects, and France is also contending with long project lead times despite efforts to streamline permitting processes.

Additionally, increased costs and rising interest rates are impacting the bankability of renewable energy projects, for instance in the US offshore wind sector. These financial barriers can lead to project cancellations and discourage further investment in the sector.

Other notable challenges are low social acceptance of renewable energy infrastructure in several regions in this cluster and a shortage of skilled installers, especially for solar PV deployment (as seen in France). Building a workforce capable of meeting demand for large-scale solar installations is essential to sustain growth in the sector.

Finally, the need to replace ageing infrastructure adds another layer of complexity, as ageing dispatchable carbon-free energy sources such as hydropower and nuclear pose an additional obstacle for this cluster. Furthermore, as these countries have been frontrunners in deploying solar PV and wind technologies, the oldest of these projects will soon require modernisation.

Cluster 2: High shares of wind and solar

Cluster characteristics

Cluster 2 countries – Australia, Germany and Italy – also exhibit a substantial solar PV and wind presence in their electricity generation profiles, surpassing even the first cluster.

Flexibility within this cluster is characterised by moderate reliance on dispatchable carbon-free energy sources. None of the countries operate nuclear power plants, nor do they currently have any policy commitments to deploy this technology. Therefore, the predominant dispatchable carbon-free resource in this cluster continues to be hydropower, particularly in Italy.

In terms of interconnectedness, Germany and Italy benefit from relatively strong interconnections with neighbouring countries, bolstering their energy security and facilitating the integration of renewable energy sources. Australia, however, does not have interconnection capacity. Nevertheless, the country's vast size and decentralised distribution of supply and demand centres, supported by adequate intrastate transmission, contribute to grid stability.

Population density is similar between Germany and Italy but notably lower in Australia. This suggests that Italy has significant potential to expand its solar PV and wind generation from a solely geographical perspective, as its conditions are at least as favourable as in Germany.

Germany and the United Kingdom are actively pursuing carbon pricing policies, enhancing their commitment to integrate the externalities associated with carbon-emitting electricity generation. In contrast, Australia's carbon pricing mechanism, implemented in 2012 under its Clean Energy Future plan, was subsequently repealed in 2014 by the newly elected government.

Screening criteria for countries in cluster 2

Cluster 2	Australia	Germany	Italy
Variable carbon-free generation share	🟢	🟢	🟢
Dispatchable carbon-free capacity share	🔴	🔴	🟡
Interconnections	🔴	🟢	🟢
GDP per capita	🟢	🟢	🟢
Population density	🟢	🔴	🔴

Notes: Dot colours correspond to the ranges defined in the screening criteria section above.

Common obstacles within the cluster

Like cluster 1, countries in this cluster face numerous obstacles hindering carbon-free energy source uptake. One of the major impediments to expansion is inadequate grid capacity and flexibility. Both Italy and Germany identify grid infrastructure as a critical challenge, and in Australia, grid constraints lead to long connection wait times for new variable renewable energy sources. Upgrading and expanding the grid is thus essential to accommodate the variability of variable renewable energy and maintain system stability. Prolonged permitting processes are also significantly delaying the deployment of carbon-free energy projects.

Additionally, countries in this cluster are approaching market saturation for variable renewables, leading to lower capture rates for wind and solar PV. This saturation has caused frequent negative-price occurrences in Australia and Germany and poses additional project financing challenges.

Cluster 3: Limited renewable energy supplies

Cluster characteristics

The cluster 3 countries of Japan and Korea have only moderate shares of dispatchable and non-dispatchable carbon-free sources in their generation mix.

Having only small shares of flexible carbon-free resources creates challenges for both countries, with Japan relying heavily on hydropower and Korea on nuclear energy. It is important to highlight the role of nuclear power as a significant carbon-free energy source in the countries of this cluster. Geographical constraints prevent cross-border interconnections in both nations, necessitating self-reliance in energy management. Korea plans to expand its nuclear power plant fleet, thereby increasing its installed capacity in dispatchable carbon-free resources, while Japan intends to maintain its current nuclear capacity in upcoming years.

High population density in Japan and Korea intensifies land availability pressures, posing additional solar PV and onshore wind deployment challenges. Effective land management solutions such as rooftop solar PV are therefore becoming increasingly crucial. While construction costs to develop offshore wind capacity in shallow waters are comparatively low, neither Korea nor Japan have extensive access to suitable areas. Instead, they both have vast wind energy potential in deeper waters, but developing it would exceed even the feasibility limits of high-cost jacket foundations, necessitating the use of more advanced and costlier technologies such as floating offshore wind systems, which would further increase project costs.

Both Japan and Korea have implemented carbon pricing mechanisms with extensive coverage, further underlining their commitment to address the externalities associated with carbon-emitting electricity generation.

Screening criteria for countries in cluster 3

Cluster 3	Korea	Japan
Variable carbon-free generation share	🟡	🟡
Dispatchable carbon-free capacity share	🟡	🟡
Interconnections	🔴	🔴
GDP per capita	🟢	🟢
Population density	🔴	🔴

Notes: Dot colours correspond to the ranges defined in the screening criteria section above.

Common obstacles within the cluster

Several obstacles common to Japan and Korea are impeding greater carbon-free energy uptake. Grid integration issues complicate expansion, and social acceptance remains a significant challenge in both countries, impacting the development of new infrastructure.

Lengthy permitting processes and complex regulatory regimes also pose significant hurdles. For example, Korea struggles with long permitting wait times, limiting opportunities for new projects, and both countries are challenged by grid connection issues.

Financing is another critical barrier. In Japan, the attractiveness of financing for renewable energy projects is counterbalanced by less favourable feed-in tariffs. Meanwhile, many of Korea’s small number of auctions for new renewable capacity additions have been undersubscribed because developers found the reference price too low.

Cluster 4: High shares of hydropower in the generation mix

Cluster characteristics

Cluster 4 – Argentina, Brazil, Mexico and Türkiye – also exhibits a medium share of carbon-free dispatchable energy sources. Argentina, Brazil and Türkiye distinguish themselves with substantial non-variable carbon-free capacity, primarily hydropower. While Mexico also uses hydropower, it has less capacity than its cluster counterparts. All cluster-4 countries operate nuclear power plants except for Türkiye, which is close to launching its nuclear phase-in.

Interconnection levels vary within this cluster. Argentina and Brazil feature robust interconnections with neighbouring countries, facilitating energy trade and enhancing system flexibility. In contrast, Türkiye and Mexico have moderate interconnection capabilities, presenting the distinct challenge of maintaining grid stability independently.

Population density also varies across this cluster, with moderate levels in Mexico and Türkiye, and lower levels in Argentina and Brazil. Regarding carbon pricing mechanisms, there is a range in cluster 4, with some countries having minimal coverage or lacking such mechanisms altogether.

Screening criteria for countries in cluster 4

Cluster 4	Argentina	Brazil	Mexico	Türkiye
Variable carbon-free generation share	🟡	🟢	🟡	🟢
Dispatchable carbon-free capacity share	🟢	🟢	🟡	🟢
Interconnections	🟢	🟢	🟡	🟡
GDP per capita	🟡	🔴	🟡	🟡
Population density	🟢	🟢	🟡	🟡

Notes: Dot colours correspond to the ranges defined in the screening criteria section above.

Common obstacles within the cluster

Despite the substantial hydropower capacity within this cluster, integrating variable renewable energy sources into the national grid is very technically challenging. The growing presence of variable renewables is exacerbating system integration issues, leading to long connection queues and extended project lead times. This situation is compounded by rising electricity demand in some countries, necessitating supply continuity and reliability and complicating the synchronisation of new renewable energy capacity with grid requirements.

High financing costs and elevated project risks are also significantly impeding renewable energy infrastructure expansion in this cluster, and Argentina and Türkiye face a distinct set of hurdles in their renewable energy sector. Financial challenges are at the forefront, with limited access to capital making it difficult to fund new renewable energy projects. If wholesale markets have been established, they suffer from low liquidity, impacting the efficiency of energy trading and market dynamics. Additionally, the poor financial health of utility companies poses a significant risk, potentially destabilising the market.

Meanwhile, sluggish permitting processes hamper the development of utility-scale solar PV projects significantly. Bureaucratic delays not only lengthen project timelines but increase costs and risks for investors. Additionally, the lack of a cohesive federal policy on renewable energy procurement, for instance in Mexico, creates an environment of uncertainty, deterring potential investors and slowing solar energy expansion.

Cluster 5: Rapidly advancing carbon-free capacity expansion

Cluster characteristics

Cluster 5, comprising China and India, has a moderate share of carbon-free energy sources in the electricity generation mix. Both countries register a medium-sized proportion of dispatchable carbon-free energy sources, with China’s share larger than India’s. Both countries operate nuclear power plants and both are actively pursuing plans to expand their nuclear power fleets.

Interconnections with neighbouring countries are limited for both China and India. However, their geographical size enables them to mitigate this constraint through domestic energy management and the construction of robust intranational transmission networks.

Regarding population density, China’s is moderate and India’s is very high, impacting the availability of land for utility-scale projects.

Both China and India have implemented carbon pricing mechanisms, although with varying levels of coverage (ranging from low to medium).

Screening criteria for countries in cluster 5

Cluster 5	China	India
Variable carbon-free generation share	🟡	🟡
Dispatchable carbon-free capacity share	🟡	🟡
Interconnections	🔴	🔴
GDP per capita	🟡	🔴
Population density	🟡	🔴

Notes: Dot colours correspond to the ranges defined in the screening criteria section above.

Common obstacles within the cluster

Similar to cluster 4, China and India need new capacity additions and could fulfil this requirement by leveraging their hydropower potential and boosting variable renewable energy contributions. While wholesale markets are in place, they suffer from low liquidity.

In China, grid integration is a challenge for new utility-scale and distributed PV projects. In India, central and state-level public entities and utility companies still suffer from financial instability, limiting their ability to procure carbon-free capacity.

Cluster 6: Significant untapped carbon-free energy potential

Cluster characteristics

The cluster-6 countries of Indonesia, Russia, Saudi Arabia and South Africa exhibit lower shares of renewable energy sources in their electricity generation mixes. Among these economies, South Africa has the highest share, although it is still relatively modest.

Flexibility within this cluster is marked by comparatively low interlinkage capabilities. Shares of variable carbon-free energy sources range from medium to small. Russia stands out because of its installed hydropower and nuclear energy capacity, surpassing 35%. In Indonesia, dispatchable carbon-free sources account for more than 15% of the installed capacity thanks to the country’s significant generation potential in hydropower, bioenergy, and geothermal energy. These characteristics influence stability and renewable energy integration within the respective systems. Whereas Indonesia and Saudi Arabia are just beginning to consider adopting nuclear power, Russia and South Africa are planning nuclear expansion.

Population density across the cluster is generally low except in Indonesia, which could encounter land availability challenges when developing utility-scale offshore renewable energy projects.

Carbon pricing mechanisms are largely absent in cluster 6, with South Africa being the notable exception.

Screening criteria for countries in cluster 6

Cluster 6	Indonesia	Russia	Saudi Arabia	South Africa
Variable carbon-free generation share	🔴	🔴	🔴	🟡
Dispatchable carbon-free capacity share	🟡	🟢	🔴	🔴
Interconnections	🔴	🟡	🔴	🟡
GDP per capita	🔴	🟡	🟢	🔴
Population density	🟡	🟢	🟢	🟡

Notes: Dot colours correspond to the ranges defined in the screening criteria section above.

Common obstacles within the cluster

This cluster is characterised by significant untapped carbon-free energy resource potential. Hydropower and geothermal make up most of the carbon-free energy portfolio, with only minimal growth in the other carbon-free technologies. The emerging economies in this cluster have only limited experience developing solar PV and wind resources.

In Indonesia, solar PV and wind deployment is hindered by overcapacity in conventional power plants and the contractual obligations of take-or-pay agreements with fossil fuel power plants. This situation locks in carbon-emitting generators and makes transitioning to renewables financially challenging. Other countries in the cluster face barriers such as macroeconomic risks, budget constraints, inadequate experience with renewable energy technologies, weak grid infrastructure, and vertically integrated, single-buyer electricity markets or wholesale markets with low liquidity, hindering their growth potential.

Emerging and developing economies face multifaceted challenges in pursuing decarbonisation

Heavy reliance on fossil fuels, particularly coal, creates a dependency that is both difficult and costly to overcome. Transitioning to cleaner energy systems demands significant investments in technology, infrastructure and institutional capacity – areas in which many emerging economies face substantial limitations.

Financial constraints remain one of the most significant barriers. In developing countries, the cost of capital is often double that of advanced economies, discouraging private and public investment in renewable energy projects. Project- and sector-specific elements, such as local regulations and policies, can account for 20-30% of the higher cost of capital in emerging markets and developing economies (EMDE). Factors such as the quality of energy institutions, sector-specific regulations, revenue reliability and the availability of infrastructure such as transmission networks and land also contribute strongly to these elevated costs. These risks, often embedded in how contracts are structured, compound the challenges.

National policymakers can take several measures to reduce the cost of capital: establish a clear vision and implementation plan for energy transitions; provide reliable data and support for project preparation; enforce strong regulatory frameworks; ensure timely permitting; and co-ordinate grid buildouts. Tailored support for new and emerging technologies can also be very useful.

Enhanced international support, including increased concessional financing, is crucial to help EMDE address obstacles and attract investment for clean energy projects. However, rapid energy demand growth – resulting from urbanisation, industrialisation and population increases – further compounds the decarbonisation challenge. Meeting higher energy demand requires not only increased capacity but also a fundamental shift towards more capital-intensive energy systems, which involve higher upfront costs but promise lower operational expenditures in the long term.

Policy and regulatory frameworks in many emerging economies are frequently inconsistent or outdated. These shortcomings deter private sector engagement and slow the adoption of renewable energy technologies. Fossil fuel subsidies further distort energy markets, creating economic disadvantages for cleaner alternatives. Infrastructure deficits, such as ageing grids that cannot support variable renewable energy sources, exacerbate these challenges. Moreover, insufficient domestic expertise and manufacturing capacity for renewable technologies increase dependency on expensive imports, limiting local economic benefits.

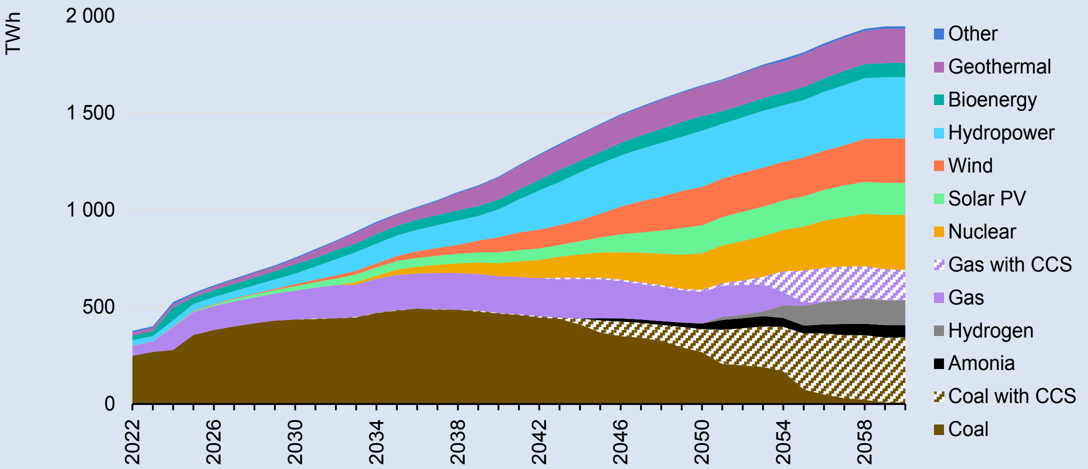
The socioeconomic implications of the energy transition present additional hurdles. Phasing out fossil fuel industries can disrupt livelihoods and local economies, making comprehensive reskilling and economic diversification programmes essential. At the same time, international collaboration, while crucial, often suffers from fragmented efforts and misaligned priorities between donors and recipients, slowing the pace of implementation.

Case study: Indonesia – challenges and pathways

Indonesia provides a compelling example of the challenges faced by emerging economies in their energy transitions. The country has set ambitious targets, including achieving net zero emissions by 2060 or earlier and increasing the share of renewable energy in its energy mix to 19-21% by 2030 and 31% by 2050. Despite these goals, implementation remains fraught with difficulties.

Reducing reliance on coal, which still fuels over 60% of Indonesia's electricity generation, will require a concerted effort. President Prabowo's commitment to phase out coal entirely by 2040 signals strong ambition, yet the latest National Electricity Supply Business Plan (RUKN) anticipates coal-fired power plants remaining in operation until 2059. Ensuring greater consistency between current planning and long-term goals will be essential to provide certainty for investors and guide Indonesia's energy transition forward.

Indonesia electricity generation by source, 2022-2060



Notes: CCS = carbon capture and storage. "Other" covers generation from diesel, ocean energies and waste heat. Values for 2022 and 2023 are historical data without industrial captive power plants.
Sources: For 2024-2060 projections, IEA analysis based on Direktorat Jenderal Ketenagalistrikan (2024), RUKN, (accessed 26 January 2025); for historical values, IEA data.

The Java-Bali grid has experienced significant overcapacity in recent years, with reserve margins exceeding 75%. This overcapacity resulted from planning based on ambitious demand growth projections that did not materialise as expected. While rising demand is expected to reduce overcapacity in upcoming years, the legacy of long-term contracts with coal plants continues to constrain system flexibility and limit the integration of new generation capacity, including renewable energy projects. Additionally, Indonesia's archipelagic geography poses unique energy distribution challenges. Decentralised solutions, such as microgrids, are critical to connect remote areas but require substantial upfront investment and logistical planning.

High financing costs further hinder Indonesia's transition to clean energy. The country's cost of capital deters private investment and inflates the overall expense of renewable energy projects. Policy delays and regulatory bottlenecks exacerbate these issues. Although the latest RUKN aims to align the power sector with National Energy Policy goals, the lengthy process for updating and issuing key energy plans (such as RUKN and RUPTL) contributes to uncertainty. Additionally, procurement, permitting and land acquisition delays continue to slow the development of utility-scale solar and wind projects.

Structural challenges also hinder renewable energy deployment. High costs, local-content requirements and supply chain inefficiencies retard progress, and social and economic considerations compound these difficulties. A rapid coal phaseout could lead to significant job losses in coal-dependent regions, highlighting the importance of robust just-transition strategies. Without such measures, there is a risk of communities being left behind in the transition to a low-carbon economy.

International funding, such as the USD 20 billion pledged through the Just Energy Transition Partnership (JETP), offers a potential pathway forward. However, translating these commitments into actionable projects has proven difficult. The contrasting projections within Indonesia's energy plans, and the lengthy process of updating key energy plans, add further complexity.

Opportunities and recommendations

To address these challenges, Indonesia and other emerging economies should consider a multipronged approach:

1. Policy and governance reforms: Establish clear and consistent regulatory frameworks to attract investment. Eliminate fossil fuel subsidies and implement carbon pricing to create a level playing field for renewables.
2. Enhanced financial mechanisms: Leverage concessional financing and blended-financing models to reduce the cost of capital. Mobilise public and private investments through international partnerships such as JETP, the Energy Transition Mechanism (ETM), and initiatives such as the ASEAN Plan of Action for Energy Cooperation (APAEC) and the Asia Zero Emission Community (AZEC).
3. Infrastructure modernisation: Upgrade grid infrastructure to accommodate higher shares of renewables and ensure interconnection across islands.

Deploy advanced technologies, including energy storage systems and smart grids, to manage the variability of variable renewable energy sources.

4. Just-transition strategies: Develop comprehensive programmes to reskill workers and diversify economies in coal-dependent regions. Foster inclusive policy dialogues to address social impacts and ensure equitable benefits from the energy transition.
5. Accelerated renewable energy deployment: Enhance procurement and simplify permitting and land acquisition processes to expedite solar and wind projects. Prioritise distributed renewable energy solutions for remote and off-grid areas to expand energy access.
6. Strengthened international collaboration: Align international funding with local needs and ensure resources are deployed effectively. Deepen partnerships to secure technical expertise and financial support, particularly for decentralised energy solutions.

Indonesia's energy transition illustrates the broader challenges faced by emerging economies while highlighting potential pathways forward. With the right mix of policies, investments and international co-operation, the country can achieve its energy ambitions, align with global climate goals and promote sustainable development.

Chapter 5. Policy recommendations to boost carbon-free energy uptake

Although efforts to reduce fossil fuel reliance have been under way for several decades (particularly since the turn of the 21st century), the share of fossil fuels in the global energy mix is declining only slowly and CO_2 emissions continue to rise. The transition to a net zero energy system is widely regarded as one of the most significant challenges faced by humankind. Achieving it will therefore require co-ordinated action from governments, businesses and civil society.

This chapter's policy recommendations, which aim to facilitate and accelerate electricity sector deployment of carbon-free energy in G20 countries, are grouped into two categories. First are general recommendations that apply universally, regardless of a country's specific context or resource endowment. The second set addresses the country clusters identified in Chapter 4, offering recommendations tailored to each cluster's unique characteristics and circumstances.

Policy recommendations for all clusters

Recognise that the carbon-free energy transition is a no-regret goal

There is broad and growing consensus among G20 countries and beyond that reducing greenhouse gas emissions is not only a necessary response to the climate crisis but also an opportunity to foster innovation and boost energy security, sustainable long-term economic growth and job creation. The G20 countries, collectively responsible for 76% of global emissions, are increasingly aware of the benefits of transitioning to a low-carbon economy.

Nonetheless, the shift away from fossil fuels towards carbon-free energy sources will not be obstacle-free. For example, unlike fossil fuels, which are dispatchable, wind and solar energy present intermittency challenges. This is a well-known issue that can and must be properly tackled, and it should not impede the transition. Furthermore, many of the technologies critical to the transition, including raw materials, metal processing and technological components, are often geographically concentrated. Proactive measures to enhance supply chain resiliency and security can reduce the threat of this recognised risk.

Another recurring challenge is the price volatility of the materials necessary for carbon-free energy development, which could make deployment costly. However, it is important to remember that fossil fuel price volatility has triggered many economic crises. While periods of elevated and volatile prices may occur during the clean energy transition, they should not derail progress.

While the green transition involves considerable challenges (e.g. securing large-scale investments; retraining workers in traditional industries; managing energy market disruptions), governments can implement policies to mitigate difficulties and provide financial support, incentives and robust frameworks for action. Multilateral collaboration, including among G20 countries, is also crucial for the sharing of best practices and financing mechanisms to accelerate progress. Despite the complexity and effort required to build a new energy system in just a couple of decades – compared with the century it took to establish the current one – the long-term benefits of transitioning to carbon-free energy systems are obvious.

Last, but not least, burning fossil fuels produces major local air pollution, contributes to climate change, and has regularly created geopolitical friction. Therefore, it is also important to acknowledge that the existing fossil fuel-based energy system is far from ideal.

Explore the best pathway to carbon-free electricity systems

As shown in our analysis of G20 countries, economies can be grouped into clusters based on distinct patterns and common characteristics. Clustering similar countries together can help them adopt suitable policy frameworks and effective strategies through the sharing of lessons learned. However, even countries with comparable natural endowments and generation mixes can have different social and political circumstances. There is therefore no single, one-size-fits-all journey towards a carbon-free electricity system.

For example, two countries with abundant dispatchable carbon-free energy might both benefit from similar strategies to promote the deployment and integration of variable renewable energy sources. However, their approaches diverge when system resilience is considered. In a country where hydropower dominates, policies must emphasise the management of water resources, seasonal fluctuations and ecosystem impacts. In contrast, a country with nuclear energy as its dispatchable carbon-free energy source will need to focus on ensuring fuel supply security, training a highly skilled workforce, addressing long-term waste management and maintaining public trust.

Furthermore, in addition to minimising generation costs, it is necessary to keep system costs as low as possible in the transition to carbon-free electricity. Implementing cost-effective solutions at the system level requires comprehensive understanding of the electricity system's specificities, such as generation mix, demand patterns, and variable and dispatchable carbon-free energy penetration.

Developing scenarios and pathways is essential to understand which combinations of technologies are most effective; identify potential challenges or bottlenecks; and advance the energy transition. These tools also offer insights into externalities, costs and investment requirements, enabling better-informed decision making. Moreover, the transition is fundamentally about and for people, making it crucial to address social dimensions such as affordability, employment impacts, and inclusivity in planning and implementation. It is essential to remember, however, that social issues vary from one country to another.

Accelerate carbon-free energy deployment

The carbon-free energy transition involves shifting from the traditional energy system to a modern, carbon-free one. Since secure electricity supplies are the foundation of modern society, it will only be possible to retire fossil fuel-based power plants if carbon-free sources can produce enough electricity to replace them. Unfortunately, barriers to carbon-free energy deployment can be numerous.

Since lengthy permitting wait times clearly prevent faster carbon-free energy deployment, streamlined permitting and simplified rules, procedures and administrative structures would accelerate uptake. For example, establishing one-stop shops to centralise and co-ordinate planning and permitting could significantly reduce the time and costs associated with developing renewable energy projects. Instituting positive administrative silence to indicate consent after response deadlines have passed could also make the permitting process more efficient. Additionally, digitalising permitting procedures for swifter communication and co-ordination would further accelerate project approvals.

It is also essential to employ adequate human resource staff with the skills necessary to administer the permitting process. Investing in training programmes to enhance the capabilities of regulatory staff and ensure they are well versed in the best practices is vital. By addressing staffing needs and ensuring that regulatory bodies are equipped to manage the demands of a growing carbon-free power sector, countries can foster a more conducive environment for the rapid deployment of carbon-free energy sources.

Public opposition is another barrier to carbon-free energy deployment, but it can be minimised or even avoided by involving local communities in renewable energy projects as early as possible. Engaging the public from the beginning of the process and guaranteeing that the social and economic benefits of renewable energy are shared widely and equitably are ways to garner support for carbon-free energy projects. Engagement can be achieved through participatory planning processes, community benefit agreements, and local ownership models. Involving communities from the outset allows developers to address concerns, build trust and create a sense of ownership, leading to smoother project implementation and reduced opposition. Furthermore, encouraging citizens to participate financially through investment opportunities can enhance community support and involvement.

It is also important to invest in spatial planning to streamline zoning and permitting procedures, and to help governments analyse environmental, social and technical characteristics to identify the most appropriate locales for renewable energy installations. Creating a dynamic spatial planning system to identify go-to or no-go areas for new installations can help avoid conflicts and ensure that projects are developed in suitable locations and on time. This proactive approach ensures that renewable energy projects can proceed without unnecessary delays, accelerating overall carbon-free energy deployment.

Address the CAPEX burden for carbon-free energy developments

Energy production is shifting from fossil fuels to carbon-free energy sources that have low variable costs (such as solar PV, wind, hydropower and nuclear). This pushes the energy sector from a system in which variable costs predominate (i.e. for fuels and for CO_2 when it is priced) to one in which most of the cost stems from capital expenditures. Addressing high financing costs and project risk is therefore critical to achieve the clean energy transition.

To this end, governments should provide a long-term schedule of regular auctions tailored to energy sector ambitions, to ensure long-term contract visibility and enable investors and developers to plan and commit resources with greater confidence. Announcing a regular schedule that reflects long-term ambitions and policy goals is crucial. Introducing large-scale, competitive long-term policy support for carbon-free energy through technology-neutral auctions could reduce project risk and secure considerable investment. Importantly, auctions should be designed to balance economic attractiveness for investors with cost minimisation for consumers and taxpayers.

It is also essential to adapt auction designs to the new macroeconomic environment, including inflationary pressures. Indexing contract prices to technology-specific macroeconomic indicators can help manage cost fluctuations and ensure project viability. If necessary, setting an appropriate ceiling price based on realistic project costs can provide additional security. Furthermore, for the success of future auctions, monitoring any obstacles to the realisation of awarded projects is important to ensure continuous improvement and successful implementation. Incentivising private sector participation in renewable energy projects and introducing national and international concessional financing options, such as microcredit schemes (in developing and emerging economies), can further support carbon-free energy sector growth in these regions.

Governments can implement several strategy options to support the energy transition. For instance, removing regulatory barriers to foster carbon-free electricity deployment through corporate power purchase agreements would unlock more diverse financing options. Another key strategy is to accelerate the phaseout of fossil fuel-fired plants in systems that have overcapacity, which can be facilitated by concessional financing and grants for early retirement and plant repurposing. Renegotiating inflexible power purchase agreements and creating a comprehensive legal, policy, regulatory and financing solution for this purpose is also essential. Enacting these measures can ensure that the transition away from fossil fuels is smooth, and that energy security and economic stability are maintained.

Furthermore, introducing policies to derisk initial exploration and development costs for renewable energy projects would make carbon-free energy installations more cost-competitive with fossil fuel-fired plants. Reducing or removing fossil fuel subsidies to level the playing field would also make carbon-free energy more attractive.

It is additionally imperative to design and implement system-friendly support mechanisms for both utility-scale and distributed carbon-free energy resources as soon as possible. Crucially, legal frameworks must lay out renewable energy curtailment rules. It is necessary to increase data transparency for economic and technical curtailment, set clear and fair curtailment rules based on electricity security, and introduce minimum full-load hours for renewable energy offtake to facilitate the integration of variable carbon-free energy sources. Plus, generation-based remuneration under long-term contracts that expose generators to market price signals should be implemented to ensure that variable carbon-free energy generators are adequately incentivised to produce energy when it is most needed.

Moreover, rewarding innovative, system-friendly solutions by introducing non-price criteria into competitive auctions can foster the development of new technologies and practices that enhance grid stability and efficiency. Implementing real-time self-consumption models and phasing out net-metering schemes can increase the system friendliness of solar PV applications, promoting more efficient energy use.

Strengthen grid infrastructure

As power grids are the backbone of the electricity system, they must have adequate capacity to advance the clean energy transition and encourage electrification. Consequently, the transition to net zero emissions must be underpinned by larger, stronger and smarter grids. At least 3 000 GW of renewable power projects, of which 1 500 GW are in advanced stages, are stalled in grid connection queues, indicating that grid bottlenecks are becoming a serious obstacle in the transition to carbon-free electricity system. Failing to undertake grid buildouts thus increases a country's reliance on imported fossil fuels and also raises the risk of economically damaging outages.

Efficient grids are essential to decarbonise electricity supplies and effectively integrate carbon-free energy sources. Moreover, modern digital grids are vital to safeguard electricity security during clean energy transitions: as shares of variable carbon-free energy sources increase, power systems need to become more flexible to accommodate changes in output. Increasingly, grids must operate in new ways and leverage the benefits of distributed resources (e.g. rooftop solar) and all sources of flexibility. For instance, grid-enhancing technologies such as dynamic tariffs can be deployed, and digitalisation can unlock the potential of demand-response systems and energy storage.

To achieve national energy and climate goals, world electricity use needs to grow 20% faster in the next decade than it did in the previous one. Electricity demand must expand even more rapidly on a global pathway to net zero emissions. Grid expansion is critical to enable these levels of growth as the world deploys more electric vehicles, installs more electric heating and cooling systems, and scales up hydrogen production using electrolysis. Meeting national goals also means adding or refurbishing over 80 million kilometres of grids by 2040, equivalent to the entire current global grid.

To meet national climate targets, grid investment needs to nearly double by 2030 to over USD 600 billion per year, with an emphasis on digitalising and modernising distribution grids. It is essential to ensure interoperability of all the different system elements and establish a pool of skilled professionals. Addressing barriers to grid development, whether they be financial, regulatory or public acceptance-related, will enable the necessary buildouts and modernisation, securing a resilient energy system for the future.

Incentivising the development of storage assets is also crucial to enhance grid flexibility, and leveraging digital technologies to integrate distributed renewable energy assets is vital. Equipping new distributed assets with digital metering capabilities can enhance monitoring and control, and using digital applications to pair distributed renewable energy assets with smart electric end-use technologies such as electric vehicles and heat pumps, can further optimise energy use and grid stability.

Grid investment challenges can be relieved by off-grid and mini-grid carbon-free energy solutions, especially in regions where extending the main grid is not cost-effective. Solar PV-plus-battery systems, for example, often produce electricity more economically than traditional diesel generators, making them an attractive option for off-grid electrification. Governments should therefore focus on removing barriers to the deployment of off-grid and mini-grid systems to give consumers in remote areas access to reliable electricity.

Overall, energy transition success hinges on comprehensive grid development, flexible regulatory frameworks, and innovative support mechanisms that together can create a resilient, efficient and sustainable energy system. Addressing these key areas can ensure that the energy grid not only supports current renewable energy needs but is also prepared for future advances and challenges. The IEA's 2023 publication on grids comprehensively assesses the current state of electricity grids worldwide, examining critical grid infrastructure elements, connection queues, outage costs, grid congestion, generation curtailment and development timelines.

Incentivise greater electricity system flexibility

While many carbon-free energy sources are available – some of them dispatchable – considerable intermittent wind and solar contributions are a common feature of electricity system transitions. It is therefore imperative to increase overall system flexibility, which depends on four key elements: supply flexibility; energy storage; interconnections; and demand response. In regions where cross-border interconnections are feasible, they provide a crucial buffer, allowing electricity to flow between neighbouring countries to balance supply and demand, improving overall system resilience and efficiency.

However, in areas where geographical or political barriers prevent strong interconnections, the other flexibility sources must be bolstered significantly. This can involve advancing storage technologies, improving demand-side management and expanding the role of dispatchable carbon-free electricity sources (e.g. hydropower, geothermal and nuclear).

Ultimately, domestic resource endowment, interconnection capacity and energy security considerations vary widely across countries, necessitating customised strategies. Policymakers must therefore analyse a country's specific needs and potentialities carefully to ensure electricity system reliability, resiliency and sustainability in the transition to carbon-free energy.

When possible, scale up dispatchable carbon-free electricity generation (hydropower, nuclear and geothermal power)

Countries with high untapped carbon-free energy potential – particularly developing and emerging economies – have the unique opportunity to leap directly to the latest carbon-free technologies. For instance, a country with significant hydropower potential should take steps to develop it because a hydropower facility's dispatchable generation – whether large- or small-scale –

can reinforce grid stability, complement variable carbon-free energy source integration and enhance electricity access.

To promote hydropower development, countries should establish robust governance structures that ensure sustainable project management, taking account of the multiple uses of water resources (i.e. for drinking, irrigation, flood control and electricity generation). Public-private partnerships can play a critical role by allocating risks appropriately among stakeholders and leveraging concessional financing to support both large-scale and off-grid projects.

For countries that choose to include nuclear energy in their clean energy transition, extending the lifetimes of existing nuclear power plants is a cost-effective way to maintain low-emissions electricity generation and grid stability. Governments should authorise lifetime extensions when safe operations can be ensured, taking advantage of existing infrastructure to avoid premature closures. At the same time, electricity markets must be designed to value dispatchable low-emissions capacity. They should provide non-discriminatory compensation to nuclear plants for their role in avoiding emissions and maintaining electricity security through services such as capacity availability and frequency control.

To support the deployment of new reactors, policymakers should establish robust financing frameworks that distribute risks equally between investors and consumers, reducing the cost of capital for projects. Accelerating small modular reactor development can also expand the role of nuclear in producing electricity, heat and even hydrogen. Investing in demonstration projects and supply chain development will be critical to realise the full potential of small modular reactors.

Additionally, governments must implement effective solutions for nuclear waste disposal, involving the public in decision making to build trust and facilitate progress. Long-term support for the nuclear industry should remain contingent on the delivery of safe, on-time and on-budget projects to maintain public confidence and maximise impact.

Similarly, countries should consider giving geothermal energy more weight in their energy policy frameworks by including it in national energy plans, setting clear goals and creating technology roadmaps that recognise it as a reliable source of dispatchable low-emissions electricity and heat. To foster early-stage project development, governments should design risk mitigation schemes in collaboration with regional, national and international financial institutions.

Policies should ensure longstanding revenue certainty and fair compensation through long-term contracts and support schemes that reflect geothermal contributions to system adequacy and flexibility. Streamlining the permitting process, including by creating dedicated geothermal permitting regimes distinct from those for mineral mining, would accelerate project deployment. Robust environmental and social safeguards must be embedded in policies through active community engagement. Improving data quality and establishing open data repositories will help attract investors by facilitating accurate geothermal resource assessments.

Expanding research, innovation and demonstration programmes will drive technological advancement, and geothermal-specific academic training and workforce development should be enlarged to meet future demand. Finally, fostering international collaboration to develop technical standards can address environmental concerns and enable large-scale production of geothermal technologies, allowing manufactures to benefit from economies of scale.

Explore the potential of bioenergy with carbon capture and storage as a dispatchable negative-emission technology

Thanks to its ability to simultaneously generate energy and remove carbon dioxide from the atmosphere, bioenergy with carbon capture and storage (BECCS) could be crucial to the clean energy transition. This technology captures and permanently stores CO_2 from processes that convert biomass into energy or fuel. Just as plants absorb CO_2 as they grow, BECCS enables the removal of CO_2 from the atmosphere while producing energy.

Targeted policies, infrastructure development and investment are critical to manufacture BECCS systems at scale to achieve commercial deployment. Thus, to accelerate BECCS deployment, governments should incentivise investment in higher-cost applications, particularly in the power and industry sectors, through measures such as tax credits, grants, contracts for difference, public procurement, and research funding. Industrial clusters, which concentrate the entire supply chain in one area – from biomass sourcing to CO_2 storage – are an attractive option for effective BECCS scaleup.

At the same time, it is essential to mitigate the environmental effects of biomass production, transport and preprocessing by addressing lifecycle emissions, land-use changes and biodiversity impacts, and by limiting fuel-food competition. Additionally, to ensure high-quality carbon removal, it is critical to implement robust monitoring, reporting and verification frameworks with standardised methodologies for assessing biogenic carbon content, storage permanence, and credit allocation across the value chain.

Consider using hydrogen technologies for energy storage

Countries aiming to enhance energy system flexibility should consider adopting energy storage solutions, including power-to-hydrogen-to-power technology. While various storage solutions compete across different time horizons, hydrogen can provide valuable flexibility over multiple time scales. Although batteries are well suited to managing daily cycles, hydrogen and thermal storage are better positioned to address longer-term needs. Although power-to-hydrogen-to-power systems can enhance seasonal flexibility, electrolysers already play a significant role in delivering flexibility, often reducing the need for full conversion back to power. In other words, electricity consumption for power-to-hydrogen conversion can help balance the grid in the right direction.

Market design reforms, including capacity remuneration mechanisms to guarantee sufficient capacity during peak demand periods and compensation for services such as ramping, are necessary to ensure system adequacy and flexibility. Targeted support for innovation is also crucial, particularly to de-risk investment in underground hydrogen storage technologies and to develop a broader range of hydrogen-firing models suited to diverse operating conditions. Furthermore, production and conversion costs need to be reduced to address the high cost of using hydrogen as an electricity storage option.

It is important to recognise that hydrogen-based electricity storage is attractive under specific conditions, but other technologies such as pumped-storage hydropower, thermal storage, gas with carbon capture, and biomass could be more cost-effective depending on system configuration and on cost developments. Ensuring the effectiveness of hydrogen within the broad mixture of energy storage solutions will require a balanced deployment approach that integrates cost reduction strategies with ongoing innovation and market development. The IEA Global Hydrogen Review assesses hydrogen production and demand worldwide, including infrastructure development, policies, regulations, investment and innovation.

Policy recommendations per cluster

Although every country must define its own clean energy transition pathway, grouping together economies with similar circumstances can enable policy alignment and collaboration. For example, while all countries must prioritise the cost-effective scaleup of carbon-free energy deployment, those more vulnerable to energy affordability challenges may need to adopt progressive tariff structures or targeted social support measures.

Cluster-specific policy priorities do not mandate the adoption of specific technologies. Thus, deploying dispatchable carbon-free capacity may involve leveraging untapped hydropower potential, expanding nuclear capacity or exploring other carbon-free options such as bioenergy with carbon capture and storage. Similarly, using energy storage to enhance system flexibility can involve a variety of technologies, including battery, pumped-storage hydropower, power-to-hydrogen-to-power, thermal energy, and compressed-air systems. While this section further highlights main policy recommendations, the country-specific policy reviews in Chapter 2 offer detailed, tailored insights.

Cluster 1: High shares of dispatchable carbon-free energy

Address ageing power plants

To safeguard electricity grid reliability while supporting the low-carbon energy transition, it is essential to evaluate the status of existing carbon-free dispatchable power plants, such as nuclear and hydropower sites. Many of these plants are ageing and may need substantial upgrades to preserve their operational efficiency, safety and further use. Prioritising the necessary investments will therefore help ensure their continued ability to provide stable power flows as shares of variable carbon-free sources increase. In addition, upgrading and awarding lifetime extensions to existing power plants instead of building new ones should be considered a cost-effective way to support energy system decarbonisation.

Use existing sites for new carbon-free facilities where possible

To expedite carbon-free energy deployment, governments should streamline permitting processes for new units built at existing power plants or brownfield sites. Many brownfield sites already have the necessary infrastructure – e.g. grid connections or access to water for cooling – that can be leveraged for new carbon-free energy installations. By simplifying permitting procedures and reducing the time and costs associated with building new units on these sites, governments can speed up the development of clean energy capacity.

Support retraining programmes for workers

As the energy sector begins to rely more on carbon-free technologies, it is crucial to support workers in fossil-based industries through retraining programmes that will help them transition to jobs in the growing carbon-free energy sector. In collaboration with industry stakeholders, governments should invest in training initiatives that equip workers with the skills needed for roles in carbon-free technologies. Preparing workers for opportunities in this expanding sector will facilitate the workforce transition, mitigating potential job displacement hardships and contributing to clean energy infrastructure development.

Cluster 2: High shares of variable wind and solar

Oversee and maintain generation adequacy, and establish capacity markets if necessary

Capacity payments, which compensate providers for maintaining available capacity, could play a crucial role in signalling the need for long-term investment in carbon-free dispatchable resources. Such mechanisms would provide a financial incentive to build and maintain flexible generation assets and energy storage technologies, ensuring these resources are available when needed. Policymakers should consider introducing or enhancing technology-neutral capacity market mechanisms that reflect the long-term value of reliability and flexibility in the power system, while also ensuring that market prices remain competitive.

Consider introducing higher granularity in short-term electricity markets

With the penetration of variable renewable energy sources such as wind and solar PV increasing, more granularity is needed in market trading windows to better manage short-term power supply volatility. The relatively coarse time granularity that is currently employed (often hourly blocks) may not fully reflect the rapid supply and demand fluctuations that can occur sub-hourly.

Introducing shorter time intervals (15-minute or even 5-minute trading products) could thus improve the efficiency of price signals, allowing for more accurate and timely balancing of supply and demand. This higher granularity would also enable the more system-friendly participation of flexibility services such as demand-side response and storage, ensuring a more resilient and cost-effective system.

Support demand and generation flexibility to respond to short-term price signals

As electricity markets evolve to accommodate higher shares of variable renewable energy, both demand and generation need to be more responsive to short-term price signals. For instance, governments could incentivise flexible demand-side resources – such as some industrial processes, smart appliances and electric vehicles – to adjust their consumption patterns to real-time price fluctuations, thereby reducing strain on the grid and enhancing cost-effectivity by adapting to supply-side time variability.

Similarly, implementing renewable energy support schemes that stimulate adjustments to market price fluctuations would incentivise generation resources to respond to price signals, enabling greater operational flexibility. Policymakers should prioritise market reforms that encourage both consumers and generators to actively respond to short-term price signals, helping balance supply and demand while minimising system costs.

Support the deployment of long-term energy storage solutions

To integrate variable renewable generation into the power grid, long-duration energy storage solutions will be critical to balance supply and demand over extended periods. Technologies such as pumped-storage hydropower, compressed-air energy storage and hydrogen storage can stock energy when variable carbon-free production exceeds demand and release it when supply is low.

However, these technologies often entail high upfront costs and long development timelines. Policymakers should therefore consider introducing capacity and energy-supply mechanisms to incentivise the development and deployment of long-duration storage solutions. These mechanisms can help reduce capital costs, attract private investment and accelerate the commercialisation of storage technologies, ensuring they become a viable option to enhance grid flexibility and reliability in the long term.

Cluster 3: Limited renewable energy supplies

Encourage space-efficient installations in densely populated areas

In regions with high population density, it is important to employ space-efficient carbon-free energy solutions to maximise clean energy potential while minimising land-use conflicts and competition. Policymakers should therefore prioritise the deployment of compact, vertically integrated renewable energy technologies such as rooftop solar panels and vertical wind turbines, which are particularly well suited to urban environments where space is limited.

Encouraging building designs to integrate renewable energy technologies, incentivising the use of urban space (e.g. rooftops, facades and industrial sites) and promoting multi-use zones can help unlock significant renewable energy potential. Additionally, targeted financial incentives – such as tax rebates, subsidies and favourable financing options – can enhance the economic viability of these installations, ensuring that space-efficient renewables contribute meaningfully to local energy needs and sustainability goals.

Urban planning regulations should be updated to accommodate rooftop solar systems and vertical wind turbines on residential, commercial and industrial buildings, while minimising regulatory barriers. Governments should also introduce specific incentives for deploying renewable energy technologies at underutilised sites such as buildings, industrial zones and brownfield areas, which are ideal locations to establish clean energy installations without new land development.

Furthermore, simplifying permitting processes for small-scale projects (e.g. residential solar panels and small wind turbines) by introducing standardised procedures can remove administrative barriers that impede adoption. Establishing dedicated units within local authorities to assist with permitting can make the process faster and more transparent, accelerating the deployment of clean energy solutions in urban and suburban settings and contributing to both energy security and environmental sustainability.

Maximise deployment of dispatchable carbon-free sources and storage

In regions that have limited interconnections with neighbouring electricity grids, system flexibility is a critical challenge for integrating variable carbon-free energy. A lack of robust interconnection infrastructure makes it difficult to balance variable generation with demand, leading to surplus generation or reliability issues. To compensate for this impediment, policymakers should incentivise the deployment of more dispatchable carbon-free energy sources such as advanced nuclear power, bioenergy and geothermal, which can provide reliable, on-demand power even when renewable energy generation is low.

Additionally, energy storage technologies, such as long-duration batteries, pumped-storage hydropower and power-to-hydrogen-to-power systems, can complement these efforts by storing excess renewable energy and dispatching it when needed. Clearly, government support for dispatchable carbon-free energy source development can both enhance grid resilience and maintain power supply reliability in areas with limited interconnections.

Consider reforming current support mechanisms for variable carbon-free energy sources

Due to falling feed-in tariffs and limited auction opportunities, the financial attractiveness of deploying variable carbon-free energy sources such as wind and solar has declined in some regions. To maintain growth in these technologies and attract new investments, policymakers should consider reforming existing support mechanisms, for example by adjusting feed-in tariffs to better reflect actual costs, but they should also find ways to improve system integration. Furthermore, while incentivising carbon-free energy deployment through measures such as financial guarantees, governments should take the need for low system costs into account and adhere to budgetary constraints.

Cluster 4: High shares of hydropower in the generation mix

Phase out fossil fuel subsidies

Gradually phasing out subsidies for fossil fuel-based electricity production can remove distortions that favour carbon-intensive energy sources, creating a level playing field for carbon-free alternatives. Plus, redirecting these funds towards financing clean energy projects can catalyse investment in solar, wind and other carbon-free technologies. Transparency and public reporting on any remaining subsidies are essential to ensure accountability and foster public trust, enabling informed decision making on the pathway to decarbonisation.

Build robust interconnections between carbon-free generation hubs and major demand centres

Investing in high-capacity transmission lines that link areas rich in solar and wind power with urban and industrial centres, where energy demand is high, can help unlock the full potential of theoretically abundant variable carbon-free energy resources. However, cross-regional collaboration and comprehensive infrastructure planning are vital to ensure grid integration, efficiency and resiliency. In parallel, promoting decentralised carbon-free energy generation in remote and underserved areas can enhance energy access and reliability, reducing dependence on fossil fuels.

Encourage the reduction of early-stage project risks

Policymakers should focus on mechanisms that mitigate uncertainties associated with financing, permitting and technology development for new projects. Governments could consider securing permits before auctions, which would simplify the process for developers and reduce initial risks. Predeveloping auction sites can also lower risks for bidders, making investments more attractive and feasible.

Strengthening institutional capacities to manage carbon-free energy projects is essential to support the growing number of renewable energy initiatives. Providing grid access guarantees for winning bidders can further incentivise investment in renewable energy projects by ensuring that any power generated will be efficiently integrated into the grid.

Incentivising private sector participation in carbon-free energy projects through enhanced frameworks for public-private partnerships, loan guarantees and streamlined approval processes can also help attract investment and make projects more bankable. Meanwhile, introducing national and international concessional financing options, such as microcredit schemes, can provide crucial financial support and security for developers. These measures collectively address most early-stage project risks.

Ensure that electricity markets function well, where relevant

In regions with wholesale markets, addressing challenges such as low liquidity can enhance market efficiency and encourage participation from a broader range of stakeholders. Reforms should aim to provide clear price signals that reflect the value of flexibility and reliability in a decarbonised grid.

Cluster 5: Rapidly advancing carbon-free capacity expansion

Eliminate financial support for coal mining and coal-fired power plants

Gradually eliminating subsidies and financial incentives for carbon-intensive energy sources will help shift investments towards renewable and carbon-free alternatives. Establishing a clear timeline for subsidy phaseout, with interim targets, can ensure a smooth transition for affected industries and communities. Redirecting funds previously allocated to coal support towards clean energy technologies, retraining programmes and economic development in coal-dependent regions is essential to minimise social and economic disruptions while fostering economic growth.

Maintain the financial viability of carbon-free projects after subsidy phaseouts

Introducing market mechanisms that provide long-term revenue certainty and enhance the bankability of carbon-free energy projects will not only incentivise investment in low-carbon technologies but also promote efficiency and innovation in the energy market. Complementary policies, including targeted grants and contracts for difference, can further support project bankability, ensuring a stable foundation for growth and contributing to overall energy sector resiliency.

Incentivise cross-border interconnection expansion

Expanding and modernising cross-border transmission lines can facilitate the sharing of carbon-free energy across regions, enhancing system cost efficiency and flexibility. Regional co-operation on interconnection projects is crucial to maximise their benefits, as collaborative planning and harmonised regulations can unlock synergies between neighbouring countries. Strengthening interconnections can bolster energy security, reduce costs and advance the global transition to a decarbonised energy system, ensuring a sustainable and equitable energy future.

Cluster 6: Significant untapped carbon-free energy potential

Reduce currency-exchange and price volatility risks

Price indexation helps mitigate inflation risks, ensuring that project viability is maintained over time. This mechanism adjusts prices in line with inflation, safeguarding the economic stability of carbon-free energy projects. Additionally, using currency indexation for international contracts protects investors and developers from exchange rate volatility, fostering financial stability for both domestic and foreign investors. These measures collectively enhance the attractiveness and security of investing in carbon-free energy technologies.

Terminate power purchase agreements that lock in power generation from fossil fuels

In prioritising carbon-free energy alternatives, policymakers should review and phase out legacy power purchase agreements that commit to fossil fuel-based power generation and block the deployment of carbon-free energy. Offering incentives for the early termination of fossil fuel-based power purchase agreements can facilitate a swifter transition, freeing up resources for investment in renewable energy projects. Such actions are critical to align energy production with decarbonisation goals and reduce the energy sector's carbon footprint.

Engage in technological partnerships and pilot projects

Initiatives in this area can build domestic knowledge and workforce skills, laying the foundation for a robust, carbon-free energy sector. Policymakers should encourage pilot projects and collaborations with experienced international partners to transfer expertise and technologies. This approach not only enhances technical knowhow but fosters innovation and the adaptation of best practices to local conditions, supporting the long-term growth of carbon-free energy infrastructure.

Develop a framework that ensures utilities remain financially viable

Particularly when utilities are monopoly companies, implementing regulatory reforms can help them maintain financial stability during the shift to carbon-free energy sources. These reforms should focus on creating a balanced regulatory environment that supports investment in sustainable energy projects. Ensuring that utilities are financially healthy and capable of making necessary investments is essential to achieve the transition to carbon-free energy.

Annexes

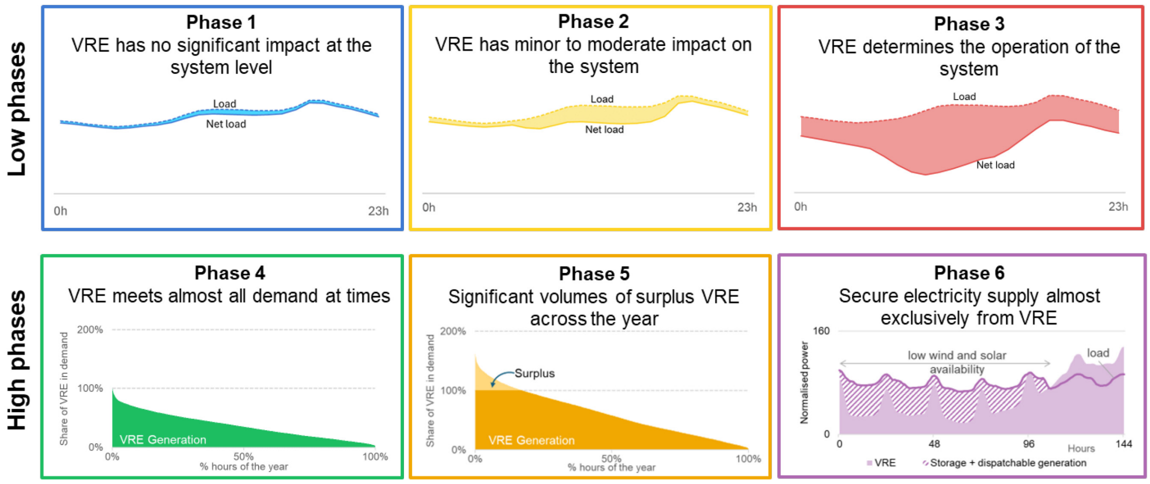
Solar PV and wind integration in G20 countries

Solar PV and wind power are becoming increasingly central to energy transitions all around the world, although these variable renewable energy (VRE) technologies present both opportunities and challenges for power systems. While some countries have successfully integrated large shares of solar PV and wind energy into their power systems, others have had less-aggressive deployment. This section explores the different approaches G20 countries have taken to navigate VRE integration based on their unique energy mixes, infrastructure, and policy environments.

IEA phases-of-integration framework

Countries are at different stages in their journeys towards full VRE integration, with the process distinguished by six key phases. Each stage represents a significant shift in how power systems manage the intrinsic variability and uncertainty of solar PV and wind energy technologies.

Description of IEA phases-of-integration framework



Notes: h = hour, VRE = variable renewable energy.

Phase 1: VRE impacts on the system are minimal. At this early stage, VRE power plants are deployed, but their influence on the broader power system is minimal. Challenges are mostly localised, affecting only the areas around the power plants and connection points.

Example: Some G20 nations such as South Africa and Indonesia are in this phase, with renewable capacity expanding but remaining a small fraction of the overall energy mix.

Phase 2: System impacts are minor to moderate. As VRE penetration increases, more frequent ramping of traditional power plants begins to affect the power system. New operational practices such as incorporating VRE forecasts become essential to maintain system reliability.

Example: Countries such as Argentina and Mexico are advancing to this phase, with traditional power assets being managed more flexibly to accommodate increasing renewable energy capacity.

Phase 3: VRE dominates system operations. In this phase, VRE becomes a key factor in power system operations. The system must adapt to frequent fluctuations, requiring the increased flexibility offered by demand-response systems, storage and enhanced grid management.

Example: Australia and Italy are approaching this phase, with wind and solar PV accounting for a significant portion of electricity generation, requiring system changes in grid operation and energy storage.

Phase 4: VRE meets most demand at times. At this stage, VRE can meet most, if not all, electricity demand during certain periods. The main operational challenge becomes maintaining system stability, especially in the aftermath of disruptions such as sudden drops in renewable energy output.

Example: Germany and the United Kingdom, having considerable VRE penetration, face grid stability challenges, particularly during periods of high VRE generation, necessitating advanced forecasting, storage solutions and grid management technologies. Other notable non-G20 countries that have reached this stage of development are Spain, Portugal and Chile.

Phase 5: VRE surpluses and systemic flexibility requirements characterise the system. Power systems in this phase regularly produce surplus VRE, requiring advanced strategies to absorb excess generation. Demand-side management, energy storage and export capabilities are key to ensure operational efficiency.

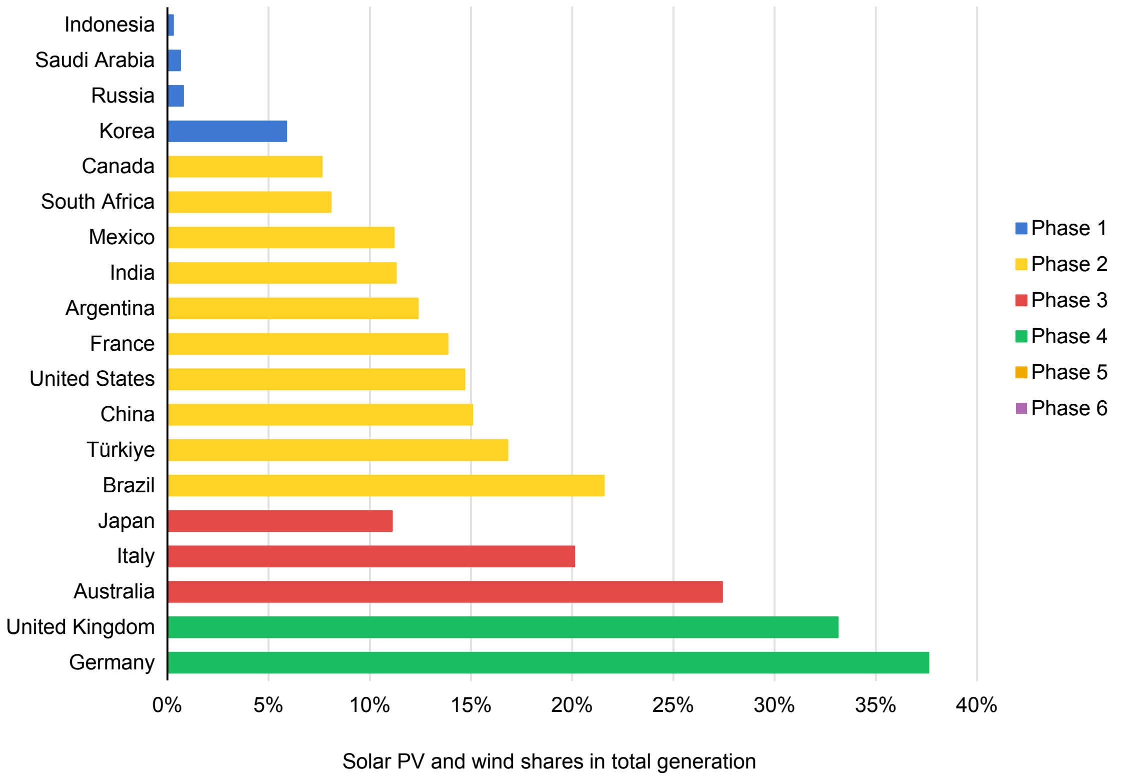
Example: Denmark, the global leader in VRE deployment, is the only country that has moved into this phase, with surplus renewable energy requiring increased demand response and exports to neighbouring countries. A notable non-G20 region in this phase is South Australia.

Phase 6: VRE is the exclusive supplier of secure energy. This phase describes systems that are engaged in procuring extremely high shares of their annual electricity supply from VRE. The main challenges at this stage include: meeting demand when wind and solar resources are unavailable for extended periods; dealing with very large VRE generation surpluses; and operating a system based largely on converted-connected resources. Effective grid management requires elaborate infrastructure, regulatory frameworks and technological innovation, which may include long-duration energy storage or extensive interregional trade.

Example: No G20 country has fully reached this stage. However, depending on the context, complete power sector decarbonisation may be possible even without realising this stage of VRE integration.

G20 country integration phases varied widely in 2023

Variable renewable energy integration in G20 countries by phase, 2023



Clustering insights vs VRE integration-phase classification

Clustering G20 countries and additionally classifying them according to the IEA VRE integration phases provides complementary perspectives for understanding challenges and opportunities in renewable energy integration. While our clustering exercise grouped countries together based on their similar system-level characteristics such as GDP per capita, solar PV and wind shares, interconnection capacity and population density, the VRE phase classification system captures their operational experiences with variable renewable energy. Upon comparison, several key insights emerge.

Cluster groups and phase alignment

Countries in more advanced phases of VRE integration (phase 4 and higher) tend to fall into clusters characterised by high solar PV and wind shares in the generation mix, substantial cross-border interconnection capacity and/or advanced dispatchable carbon-free technologies. For instance, countries such as Germany and the United Kingdom demonstrate high alignment between their advanced operational practices and the clustering metrics.

Unique characteristics highlighted by clustering

Certain clusters have unique characteristics that help explain deviations in phase classification. For example, Japan's classification in phase 3, despite its relatively modest VRE share, aligns with its unique system constraints (e.g. limited regional interconnections) that necessitate advanced operational adjustments. This contrasts with countries such as France and Mexico, which remain in phase 2 even though their VRE penetration is comparable or higher.

Policy and structural contexts

The clustering exercise also revealed structural and policy-related factors that influence a country's phase classification. Countries with high per-capita GDP and robust interconnection capacity, such as members of the European Union, benefit from co-ordinated policies that accelerate the integration process. Meanwhile, countries with lower population densities and abundant land availability, such as Australia, exhibit distinct VRE growth patterns within their clusters but may still face operational challenges.

Outliers: Korea vs Japan – explaining the difference in VRE phase classification

Comparing the energy systems of Korea and Japan is a valuable learning opportunity. Korea, with its relatively low VRE share and phase 1 classification, may benefit from insights into how Japan's operational challenges have led it to reach phase 3 with relatively low VRE penetration (compared with countries such as Mexico and France).

Korea is classified as being in phase 1 of VRE integration, reflecting its current early-stage deployment of renewable energy and system adaptation. With approximately 6% VRE in its power generation mix, Korea's power system may experience some localised challenges related to the variability of renewable energy. However, at this penetration level, these effects are generally not significant enough to impact broader power system operations, unless the resources are heavily concentrated in one single region. Several factors influenced Korea's phase-1 classification:

- **Low VRE penetration.** The country's relatively low VRE share means that the power system does not yet face widespread operational challenges such as steep ramp-ups or balancing requirements.
- **Geographical constraints.** Korea's limited land area reduces spatial diversity in renewable energy production, which might hinder the natural balancing effects of larger systems in which solar ramp-ups do not occur simultaneously, and wind patterns differ across regions.
- **Policy and infrastructure readiness.** Korea is still in the process of adopting the operational frameworks and building the infrastructure necessary for higher levels of VRE integration, such as enhanced grid flexibility and energy storage.

In contrast, Japan is classified as phase 3, with a comparatively higher VRE share (11% compared with Korea's 6%). This classification reflects Japan's system challenges and its need for more advanced adaptations to renewable energy variability, driven by both necessity and system characteristics.

One key factor is the country's regional grid structure. Inadequate regional interconnectedness amplifies the operational challenges posed by VRE, with advanced measures required to ensure stability even at moderate penetration levels. Additionally, solar PV dominates Japan's VRE mix, creating significant ramping challenges and midday peaks that place a strain on grid operations. Japan has therefore implemented advanced grid-management tools, including demand-side response, improved forecasting and storage solutions to address its VRE integration challenges. Both its challenges and efforts have accelerated its advancement to phase 3.

Moreover, the Japanese government's proactive approach to renewable energy integration, coupled with early investments in technology and infrastructure, has enabled a smoother transition despite structural challenges.

Outlook for Korea

By 2030, Korea is expected to have advanced to phase 2 or 3 of VRE integration because higher shares of solar PV and wind in the generation mix will necessitate the adoption of advanced operational measures. Additionally, Korea's compact geography, similar to Japan's, means that VRE production patterns will remain relatively homogeneous, creating system-wide challenges that will require co-ordinated responses. Korea's VRE growth is also expected to be dominated by solar PV, which will introduce ramping and balancing challenges like those faced by Japan.

Furthermore, investments in energy storage, grid flexibility and interconnection capacity will be critical to support Korea's transition to later phases of integration.

Abbreviations and acronyms

AC	alternating current
APS	Announced Pledges Scenario
ASEAN	Association of Southeast Asian Nations
AU	African Union
BECCS	bioenergy equipped with CCUS
CAPEX	capital expenditure
CCfD	carbon contracts for difference
CCGT	combined-cycle gas turbine
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
CfD	contract for difference
CFE	carbon-free energy
CHP	combined heat and power
CO_2	carbon dioxide
CO_2-eq	carbon-dioxide equivalent
COP	Conference of Parties (UNFCCC)
CSP	concentrating solar power
DC	direct current
DoE	Department of Energy (United States)
DSO	distribution system operator
DSR	demand-side response
EMDE	emerging market and developing economies
ETS	emissions trading system
EU ETS	European Union Emissions Trading System
EU	European Union
FID	final investment decision
FiT	feed-in tariff
FY	financial year
GCP	Gas, Coal and Power Market Division (IEA)
GDP	gross domestic product
GHG	greenhouse gases
GT	gas turbine
H_2	hydrogen
IEA	International Energy Agency
IHTF	International Hydrogen Trade Forum
IMF	International Monetary Fund
KEEi	Korea Energy Economics Institute
LCOE	levelised cost of electricity
MER	market exchange rate
MOTIE	Ministry of Trade, Industry and Energy (Korea)
MoU	Memorandum of Understanding
NDC	Nationally Determined Contribution
NECP	National Energy and Climate Plan (European Union)
NPV	net present value

OCGT	open cycle gas turbine
OECD	Organisation for Economic Co-operation and Development
OPEX	operating expanses
PPA	power purchase agreement
PPP	purchasing power parity
PV	photovoltaics
R&D	research and development
RES	renewable energy sources
REZ	renewable energy zones
SME	small and medium enterprises
SMR	small modular reactors
TSO	transmission system operator
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
VALCOE	value-adjusted levelised cost of electricity
VAT	value added tax
VRE	variable renewable energy
WACC	weighted average cost of capital
WEO	World Energy Outlook

Units of measure

Area	km^2	square kilometre
Distance	km	kilometre
Emissions	t CO_2	tonnes of carbon dioxide
	kg CO_2-eq	kilogrammes of carbon-dioxide equivalent
Energy	kWh	kilowatt-hour
	MWh	megawatt-hour
	GWh	gigawatt-hour
	TWh	terawatt-hour
Mass	kg	kilogramme
	t	tonne (1 tonne = 1 000 kg)
	kt	kilotonne (1 tonne x 10^3)
	Mt	million tonne (1 tonne x 10^6)
Monetary	USD million	1 US dollar x 10^6
	USD billion	1 US dollar x 10^9
	USD trillion	1 US dollar x 10^{12}
	USD/t CO_2	US dollars per tonne of carbon dioxide

Power	W	watt (1 joule per second)
	kW	kilowatt (1 watt x 10^3)
	MW	megawatt (1 watt x 10^6)
	GW	gigawatt (1 watt x 10^9)
	TW	terawatt (1 watt x 10^{12})

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