REN21
RENEWABLES NOW

RENEWABLES 2023
GLOBAL STATUS REPORT

ENERGY SYSTEMS & INFRASTRUCTURE

2023
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FOREWORD

Energy systems and infrastructure are the bridges between energy demand and energy supply. Energy systems – including storage, digitalisation, sector coupling, demand-side management and regional interconnections – enable energy to be efficiently managed and transported where needed. This is particularly critical considering the record growth of solar photovoltaics and wind power generation documented in the recently launched *Supply Module of the Renewables 2023 Global Status Report Collection*.

Like any solid bridge, energy systems and infrastructure require forward thinking, political vision, robust planning and substantial upfront investments. This module focuses on the intricacies of ensuring system inertia, the role of forecasting techniques, managing grid congestion and others. It also looks at the pivotal role of energy policies in improving grid quality and reliability, as well as the need for energy storage capacity and regional integration of energy systems. Countries investing in national and regional energy systems and infrastructure have achieved higher levels of renewable energy penetration compared to those that have not.

As we celebrate the recent achievements in renewable energy and take stock of the road ahead, it is essential to understand the central roles of energy systems, infrastructure and parallel investments in achieving extensive deployment of renewables. I want to thank the REN21 team, the authors, special advisors and contributors who have given their expertise and time in producing this module. I trust that this module will provide the necessary insights and data to empower policy makers, industry leaders and stakeholders to fast-track the energy transition with renewables.

Rana Adib
Executive Director, REN21

REN21
RENEWABLES NOW

RENEWABLE ENERGY POLICY NETWORK
FOR THE 21st CENTURY

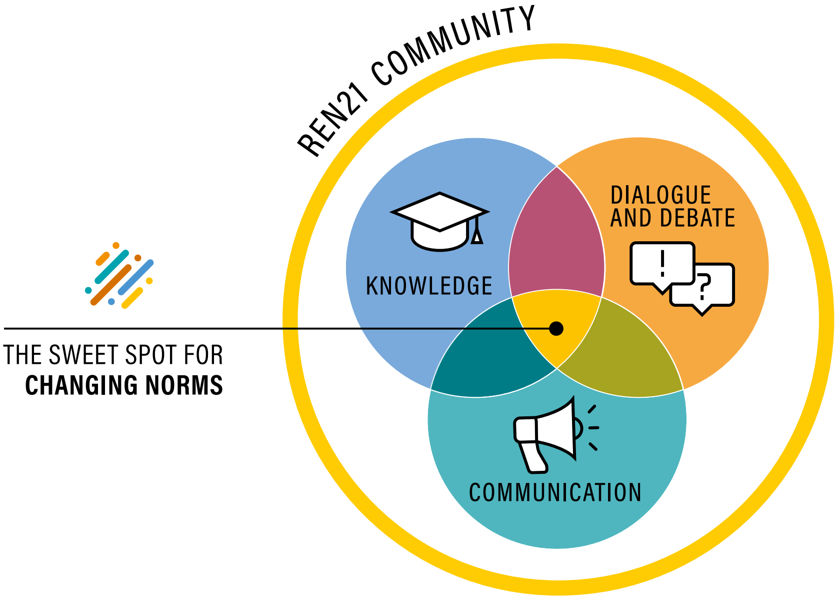
REN21 is the only global community of actors from science, governments, NGOs and industry **working collectively** to drive the rapid uptake of renewables – now!

REN21 works to build knowledge, shape dialogue and debate, and communicate these results to **inform decision makers** to strategically drive the deep transformations needed to make renewables the norm. We do this in close co-operation with the community, providing a platform for these stakeholders to engage and collaborate. REN21 also connects with non-energy players to grow the energy discourse, given the economic and social significance of energy.

The most successful organisms, such as an octopus, have a **decentralised intelligence** and "sensing" function. This increases responsiveness to a changing environment. REN21 incarnates this approach.

Our more than **4,000 community members** guide our co-operative work. They reflect the vast array of backgrounds and perspectives in society. As REN21's eyes and ears, they collect information, share intelligence and make the renewable voice heard.

REN21 takes all this information to better understand the current thinking around renewables and change norms. **Our publications** are probably the world's most comprehensive crowd-sourced reports on renewables. Each is a truly collaborative process of co-authoring, data collection and peer reviewing.



CROWD-SOURCED DATA AND KNOWLEDGE

REN21's data and knowledge collection method is built on a global multi-stakeholder community of experts. It is validated in a collaborative and transparent open peer-review process. It is made openly available to develop a shared language that shapes the sectoral, regional and global debate on the energy transition.

REN21
CROWD-SOURCED DATA
AND KNOWLEDGE

For more information, see the Methodological Notes section on data collection and validation.

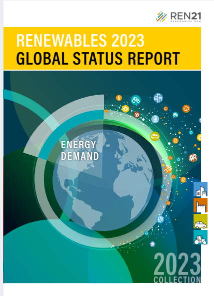
RENEWABLES GLOBAL STATUS REPORT

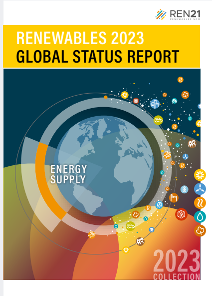
2023 COLLECTION

Since 2005, REN21's *Renewables Global Status Report* (GSR) has spotlighted ongoing developments and emerging trends that shape the future of renewables. It is a collaborative effort involving hundreds of experts.

This year's edition (18th) has evolved in design and structure to reflect the fundamental changes in the global energy landscape. The new structure is in the form of a collection of five publications. In addition to presenting the trends in renewable energy supply, it also dives into the energy demand sectors, with dedicated modules on buildings, industry, transport and agriculture. It includes a publication on energy systems and infrastructure with renewables, as well as a publication on renewables for economic and social value creation, acknowledging the key role that energy plays across economies and societies. Collectively these five publications offer readers a systemic global overview of the current uptake of renewables.

This new structure makes the GSR a key tool in expanding the renewable energy discussion into key sectors and ecosystems, developing a shared language and driving a stronger integration of supply, demand, infrastructure, markets and investment.





Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

Federal Ministry
for Economic Cooperation
and Development

This report was commissioned by REN21 and produced in collaboration with a global network of research partners. Financing was provided by the German Federal Ministry for Economic Cooperation and Development (BMZ), the German Federal Ministry for Economic Affairs and Climate Action (BMWK) and the United Nations Environment Programme. A large share of the research for this report was conducted on a voluntary basis.

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REN21 releases issue papers and reports to emphasise the importance of renewable energy and to generate discussion on issues central to the promotion of renewable energy. While REN21 papers and reports have benefited from the considerations and input from the REN21 community, they do not necessarily represent a consensus among network participants on any given point. Although the information given in this report is the best available to the authors at the time, REN21 and its participants cannot be held liable for its accuracy and correctness.

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REPORT CITATION

REN21. 2023. *Renewables 2023 Global Status Report Collection, Renewables in Energy Systems & Infrastructure*
(Paris: REN21 Secretariat).

ISBN 978-3-948393-09-0

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→ Glossary
→ List of Abbreviations

Reference Tables can be accessed through the
GSR 2023 Energy Systems & Infrastructure Data Pack at
→ http://www.ren21.net/gsr2023-data-pack/systems

For further details and access to the report, references and endnotes, visit **www.ren21.net/gsr-2023**

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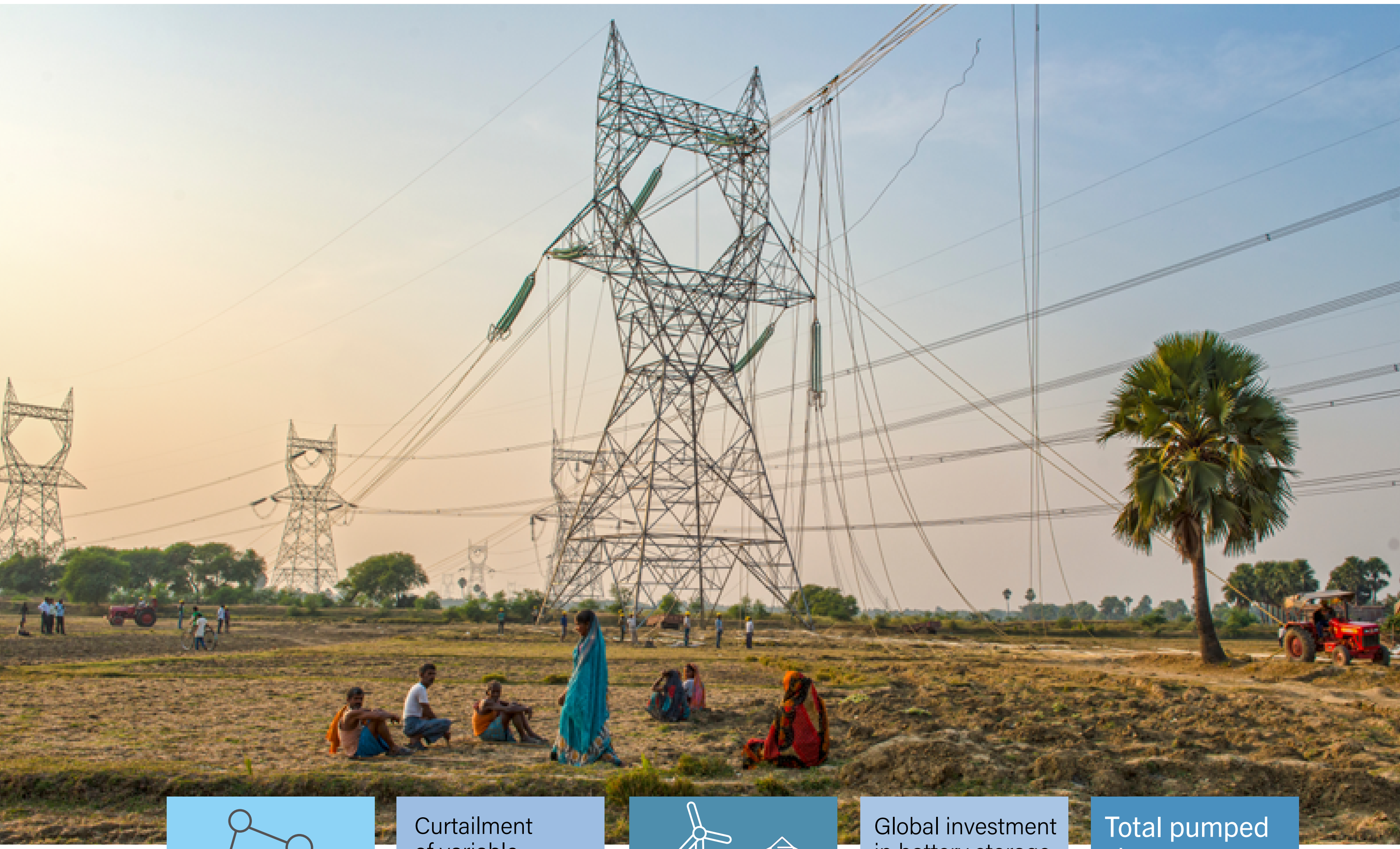


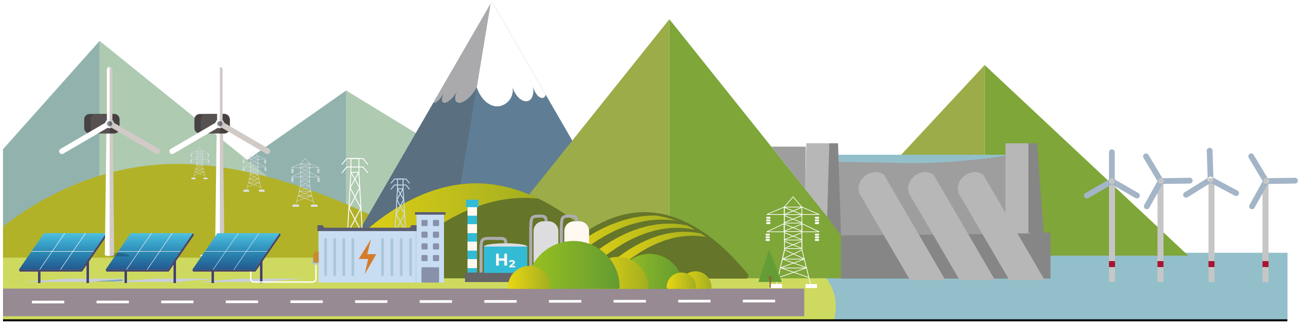
Virtual power plants continue to expand in Europe, with a total installed capacity of nearly **50 GW.**

Curtailment of variable renewable energy is still occurring due to a lack of transmission and storage capacity, inadequate planning and land management challenges.

More than **1,000 GW** of solar and wind power projects were stuck in permitting and interconnection queues as of 2022.

Global investment in battery storage capacity totalled **15.7 USD billion** in 2022.

Total pumped storage capacity increased by **10.5 GW** in 2022, for a global total of 175 GW.



RENEWABLE ENERGY SYSTEMS & INFRASTRUCTURE

Module Overview | Policy | Investment | Market Developments

MODULE OVERVIEW

In 2022, the energy sector was marked by disruptions in supply, rising energy prices, and record deployment and investment in renewables. As fundamental changes reshape the global energy system, policy makers, grid operators and investors are becoming more aware of the role that renewable energy plays beyond mitigating climate change. Among the key benefits that renewables can bring to a new energy system are energy security, economic and social value creation, and, potentially, greater geopolitical stability.

The share of renewables in the global energy mix continues to rise, reaching 12.7% of total final energy consumption (TFEC) in 2021 and 30% of power generation in 2022.[1] These trends are creating irreversible momentum for a global energy transformation. Although surges in wind power, solar photovoltaics (PV) and other renewables have taken place mostly in the electricity sector, technology developments in heat pumps and electric vehicles are extending the deployment of renewables in other key sectors such as transport, industry, buildings and agriculture. Innovations in digitalisation, growth in energy storage and the crucial role of grid interconnection are expanding the potential for renewables to flourish in ways that were unimaginable just a decade ago.

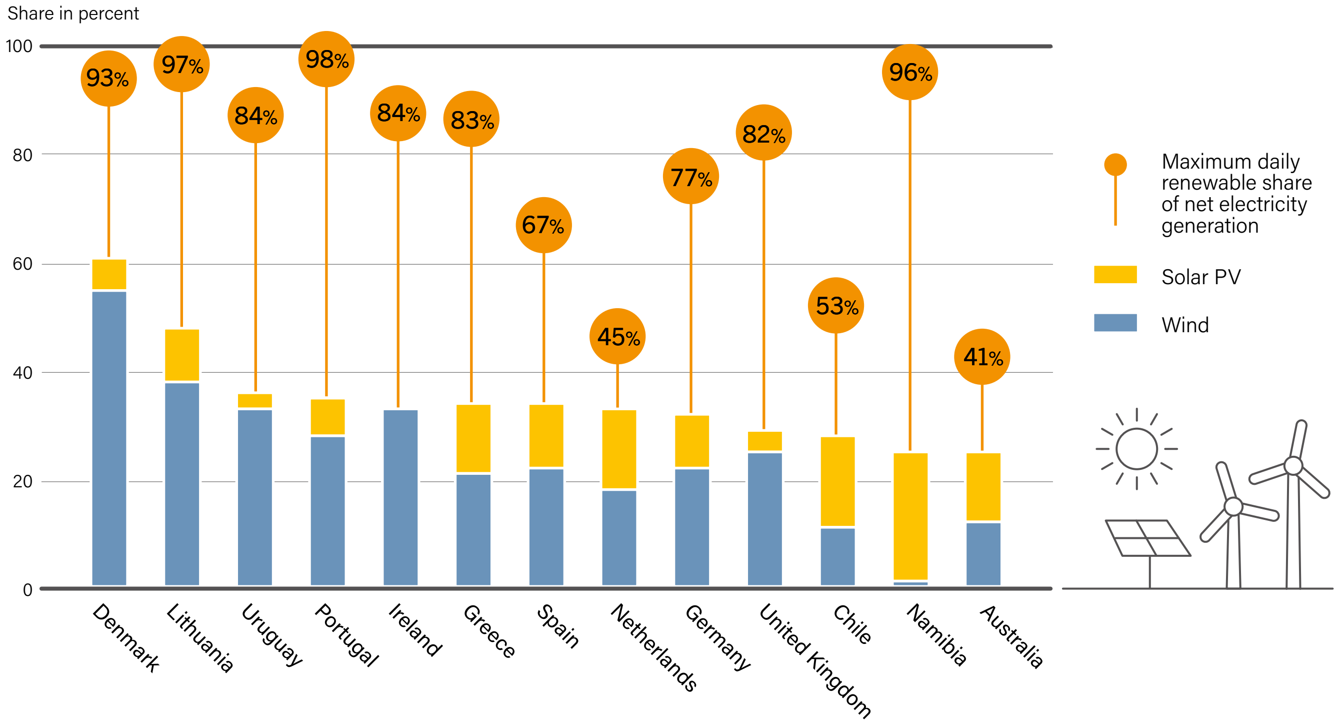
Renewable energy technologies have come a long way in just 20 years, especially through the rapid growth of solar PV and wind power. Driven by technological advancements, declining costs and growing concerns about fossil fuels (environmental and climate concerns, price volatility and supply disruptions), these variable renewable energy technologies – which can fluctuate in their output depending on weather patterns and other variables – have rapidly gained momentum. In 2022, the world's total installed capacity of solar PV grew by 243 GW and of wind power by 77 GW.[2]

The share of variable renewables in global electricity generation exceeded 12% for the first time ever in 2022.[3] Several countries have seen much higher shares, including Denmark with 61% of gross electricity from renewables (55% wind, 6% solar PV), Uruguay with 36% (33% wind, 3% solar PV), Portugal with 35% (28% wind, 7% solar PV), Greece with 34% (21% wind, 13% solar PV) and Germany with 32% (22% wind, 10% solar PV).[4] (→ *See Figure 1.*) On a daily basis, the maximum renewable share (including wind, solar, hydropower and other renewables) of net electricity generation reached as high as 98% in Portugal, 97% in Lithuania, 84% in Ireland and 82% in the United Kingdom.[5]

However, integrating and expanding renewables to achieve high shares in utility grids remains a major challenge. Effective grid integration requires technology development, supporting policies, increased investment and co-ordination among different stakeholder groups. The variable nature of solar and wind power can affect system stability, making it more difficult to balance supply and demand. This is especially true as electricity demand is expected to rise an estimated 2-3% annually from 2021 to 2030.[6] This increase is related to greater electrification of end-uses, growing populations and incomes in developing economies, and the surging demand for space cooling as temperatures rise.[7]

FIGURE 1.

Top Countries for Share of Variable Renewable Electricity Generation, and Maximum Daily Renewable Share of Net Electricity Generation, 2022



Source: See endnote 4 for this module.

Given the variable nature of solar and wind energy, grid operators are unable to fully dispatch[i] this renewable output in the electricity system. As a consequence, in 2021 grid operators in the United Kingdom curtailed 7 terawatt-hours (TWh), or 4%, of the country's annual wind power generation.[8] In Germany, nearly 5.4 TWh was curtailed in 2022, down from a record high of 6.4 TWh in 2019.[9] In the United States, the California Independent System Operator (CAISO) curtailed 1.4 TWh of utility-scale solar power in 2020, representing 5% of total production.[10] However, key solutions exist to increase dispatching options for operators and to decrease the curtailment of renewable electricity, including energy storage, sector coupling, demand-side management and improved forecasting techniques.

Energy storage technologies can help tackle the variability of wind and solar energy by storing surplus energy generated during times of high output but low electricity demand, and then making it available during times of lower output but high electricity demand.[11] Integrating energy storage systems, such as pumped storage and batteries, with variable renewable energy can provide better balance to the overall system, depending on the grid operator requirements. Utility-scale storage capacity ranges from several to hundreds of megawatt-hours. Lithium-ion (Li-ion) batteries have become the most prevalent and mature battery storage type, driven largely by declining technology costs spurred by the growing demand for Li-ion batteries in electric vehicles.[12]

Sector coupling can integrate energy supply and demand across different electricity, heat and transport applications. It facilitates higher shares of renewables by providing the system flexibility required by variable renewable energy.[13] Sector coupling uses excess power generation at peak times, preventing it from being wasted, optimising system operations and increasing efficiency.[14] This is achieved mainly through linking the power sector with heating/cooling (to meet thermal needs) and with transport (to charge electric vehicles). However, other applications such as power-to-hydrogen transformations also are being explored.[15] (→ *See GSR 2023 Demand Modules.*)

Digital technology can improve the energy system's reliability by integrating monitoring, analysis, modelling and autonomous decision making. **Demand-side management or demand response** improves the flexibility of the power system and is facilitated by digital technology integrated in a widening array of smart appliances, such as smart meters, controllable thermostats and electric heat pumps. Through approaches such as time-of-use electricity tariffs, real-time pricing, day-ahead scheduling, and energy efficiency incentives, grid operators can in principle influence the load profile by shifting or reducing energy use during periods of low renewable energy production

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[i] Dispatchable generation refers to sources of electricity that can be programmed on demand at the request of power grid operators, according to market needs.

or high demand. The benefits of demand-side management are potentially two-fold: 1) system operators can benefit from the shift in energy use from peak to non-peak hours, and 2) consumers can reduce their electricity bills by adjusting the timing and amount of electricity use (depending on system design).[16]

Improved forecasting techniques can help grid operators anticipate and respond to fluctuations in renewable energy output more effectively through better management of power generation and transmission resources, helping to maintain grid stability. Digitalisation is playing a growing role in energy systems dominated by generation from variable renewables. It aims to exploit and leverage the physical capabilities, or hardware components, of the system (such as the sensors of a weather station), together with the software capabilities (such as the algorithms used to forecast the weather conditions for a defined time horizon).

Data analytics in weather forecasting uses statistical methods in numerical weather and climate predictions to represent uncertainty, reduce bias and improve representation of long-term climate variability more accurately. Weather forecasting techniques predict the weather ahead of time, helping to improve future dispatching of conventional energy resources and to balance out the intermittent generation from renewables. From a techno-economic standpoint, forecasting helps to maximise the system technical performance (imbalance of supply and demand) while minimising the overall cost (dispatching the most economical thermal unit).[17]

Energy storage optimisation works best in competitive markets by leveraging the power of real-time data analytics. In markets where real-time pricing or day-ahead scheduling apply, optimisation techniques can inform operators about whether they should 1) store renewably generated energy or buy from the utility grid (due to low inflow prices); 2) use renewably generated energy (due to high inflow prices); or 3) inject it into the grid (due to high resale prices for grid in-feed). These techniques increase the value of storage resources for both grid operators and end consumers.

Dynamic line rating technology makes it possible to monitor the real-time capacity of transmission lines and to adjust accordingly the amount of electricity being transmitted. These and other transmission solutions can help prevent curtailment of renewable energy sources and reduce congestion on the grid.[18]

Complementing these solutions, there is a need for adequate and **reliable grid infrastructure**, including electric grids, district heating and cooling networks, and pipelines to facilitate the transmission of renewable gases such as hydrogen, ammonia and synthetic methane. The expansion and careful planning of transmission and distribution networks are necessary to avoid bottlenecks that delay (or potentially halt) the feeding of more renewables into the network.[19] This can be a costly and time-consuming process, requiring careful planning and co-ordination with local communities and stakeholders.[20] (→ *See Sidebar 1.*)

In many cases, large centralised renewable energy plants (such as offshore wind farms) are located in remote areas far from demand centres. This can lead to grid congestion, as the transmission lines required to transmit the electricity to areas of demand may be inadequate. Grid improvement plays a key role in overcoming such bottlenecks and connecting new renewable energy capacity. Accelerating the permitting process also is critical for developing and connecting renewables to the grid. Across the United States and Europe, an estimated 1,000 gigawatts (GW) of solar projects was reportedly stuck in the interconnection queue as of 2022, close to four times the amount of new solar capacity installed globally that year.[21] Meanwhile, more than 500 GW of wind power was waiting to be connected to the grid, more than five times as much as was installed during the year.[22]

Regional interconnection improves the security of the electricity supply and helps integrate more renewables into the energy system. It lowers the risk of power blackouts, reduces the need to build new power plants and makes it easier to manage variable renewable energy. **Long-distance interconnectors**, such as high-voltage direct current transmission lines, can be used to transport electricity over long distances, with relatively low losses.[23] They can help relieve congestion in areas with high levels of renewable energy generation and low demand.[24] (→ *See Snapshot: Germany.*)

Finally, with **non-variable renewable energy plants** – such as hydropower, geothermal, concentrated solar thermal power (CSP) with thermal storage, and biopower – the power output can be controlled to meet signals imposed by the operator to ensure that the supply meets the load requirements.

Despite the integration challenges, the many benefits of adding renewable energy into utility grids are increasingly being acknowledged. Renewables not only help to reduce greenhouse gas emissions, but also can create new jobs and economic opportunities in local communities.[25] As renewable energy continues to expand globally, it is important to address the challenges head-on and to develop innovative solutions that enable the world to achieve its targets for net zero greenhouse gas emissions.

This module discusses some of the notable challenges[i] in expanding renewables, along with corrective solutions and related policy advancements, investments and other developments in 2022.

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[i] This list is not exhaustive but rather aims to show developments in the field to integrate more renewables into utility grids.

SIDEBAR 1. Improving Grid Quality

Traditional power systems that rely on fossil and nuclear power units or on hydropower have consisted exclusively of rotating machines for electricity generation. These machines were designed to rapidly adjust their output levels in response to fluctuations in demand or load, which is tightly coupled to the system frequency. In contrast, variable renewable energy technologies rely on (non-rotating) power inverters[i]. This greatly affects the overall system inertia, requiring fast-reacting conventional plants to balance between supply and demand during times when the availability of renewable energy fluctuates (for example, when the sun is not shining or the wind is not blowing). Key proposed solutions to support grid reliability include synthetic (virtual) inertia, synchronous condensers and grid-forming inverters.

Synthetic inertia is achieved via power electronics controllers that can adjust the output of renewable energy sources in response to changes in system frequency, mimicking the stabilising effect of traditional rotating mass. By providing synthetic inertia, power system operators can improve the stability and reliability of grids even as they integrate increasing shares of variable renewable energy generation.

Synchronous condensers are rotating machines whose shaft is not connected to anything, but instead spins freely. The purpose is not to convert electric power to mechanical power or vice versa, but to adjust conditions in the utility grid – for example, providing short-circuit power, inertia or voltage recovery during faults. Synchronous condensers can be introduced in the network as newly added assets but also can entail repurposed retired generators. By repurposing power plants that may otherwise become stranded assets, the generator units can serve as synchronous condensers to supply system inertia to the grid.

Grid-forming inverters, also based on power electronics, operate autonomously and provide stable, grid-like voltage and frequency, even in the absence of a strong grid connection. This can help to improve the local grid stability (off-grid and islanded) in systems with low inertia.

[i] Inverters are power electronic devices that consist of switches to convert between alternating current (AC) and direct current (DC). They are an essential component in integrating renewables into utility grids.

Source: See endnote 20 for this module.

SNAPSHOT

GERMANY

Alleviating Grid Congestion Through Investments in Transmission Infrastructure

Grid congestion and electricity curtailment have become significant challenges for Germany as the country continues its energy transition. Germany has an abundance of wind energy in the north, particularly during the winter months, and a surplus of solar energy in the south during the summer. Efficiently transmitting this energy to the areas where it is needed most is crucial to optimising the use of this renewable generation.

A main barrier to addressing grid congestion in Germany is the slow pace of commissioning sufficient transmission infrastructure, due to technical, regulatory and financial challenges. Another major hurdle in developing new transmission lines is public opposition from groups concerned about the visual impacts, potential health risks and effects on property values. As a result, the approval process for high-voltage transmission projects can be lengthy and contentious, further delaying the construction of infrastructure.

The German government has taken several regulatory and legal actions to improve transmission infrastructure and address grid congestion challenges. German transmission system operators engage with close and personal dialogue consultation to increase social acceptability and minimise impacts on nature and society. Significant steps included enactment of the Power Grid Expansion Act (Energieleitungsausbaugesetz or EnLAG) and the Grid Expansion Acceleration Act (Netzausbaubeschleunigungsgesetz Übertragungsnetz or NABEG), which were designed to accelerate the expansion and modernisation of grid infrastructure. The EnLAG identified 24 priority transmission projects, including building new high-voltage lines and upgrading existing lines, and the NABEG aims to streamline the planning and approval processes for these projects, reducing bureaucratic hurdles and accelerating grid expansion.

Source: See endnote 24 for this module.

POLICY

By the end of 2022, a total of 57 countries and sub-national jurisdictions as well as the European Union (EU) had adopted or announced policies focused on energy systems and infrastructure for the optimal use of renewables.[26] Of these, 41 jurisdictions had policies for **energy storage** (including 20 fiscal/financial policies), 5 for **grid infrastructure** and 11 for **electric vehicle charging infrastructure**.[27] Policies around **renewable hydrogen** for energy storage also gained momentum. When co-ordinated, these solutions can represent vast opportunities for increasing grid reliability and the quality and security of electricity supply.

Only 11 countries and sub-national jurisdictions had in place specific targets for energy storage capacity, whether for pumped (hydropower) storage or battery storage.[28] During 2022, Greece released its new Energy and Climate Plan, increasing the country's storage target from 3 GW to 7 GW by 2030.[29] At the sub-national level, the state of Victoria in Australia announced a target of 6.3 GW of renewable electricity storage by 2035, including batteries, pumped storage and hydrogen production through electrolysis for energy storage, with the goal of powering half the state's homes at peak energy use.[30] In the United States, California increased its energy storage target from 75 GW to 85 GW by 2035; Maryland set a goal of 3 GW of storage by 2033; and New York doubled its energy storage target to 6 GW by 2030.[31]

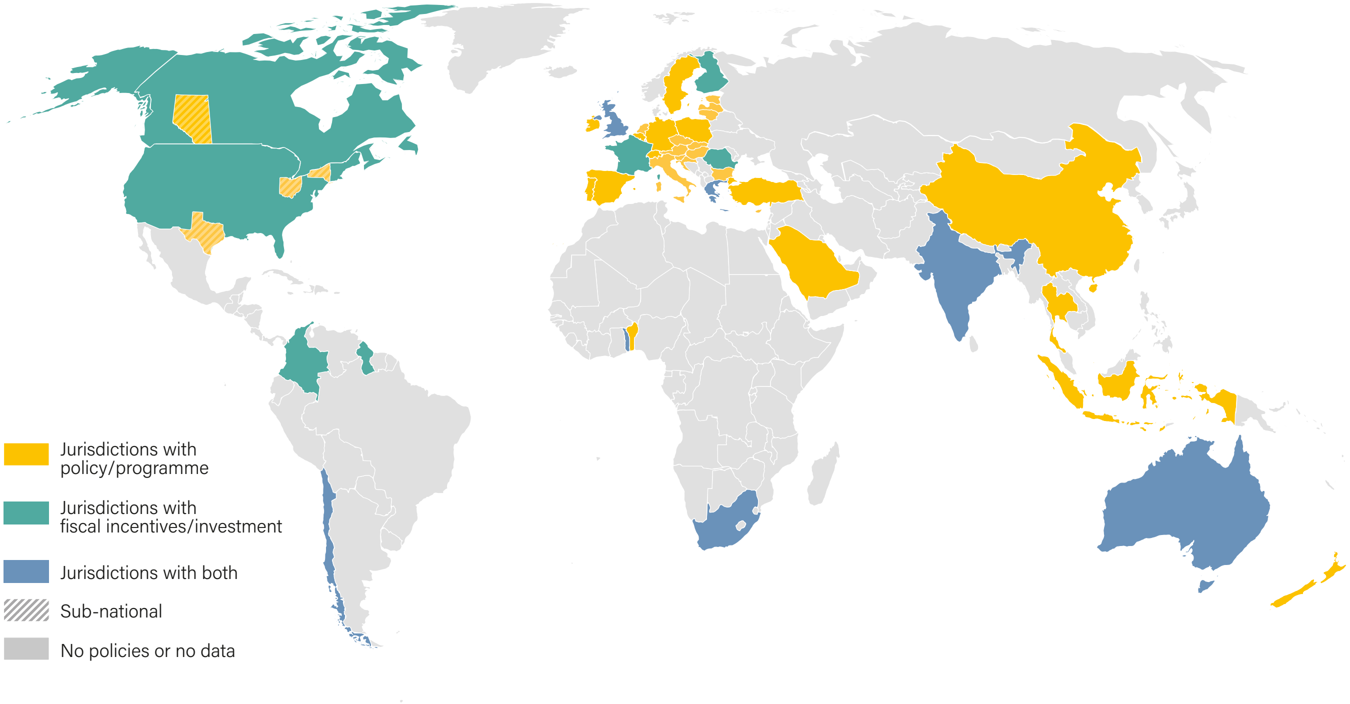
Fiscal and financial incentives for energy systems and infrastructure increased during 2022. The US Inflation Reduction Act provided an investment tax credit for stand-alone energy storage.[32] Israel introduced a distinct favourable tariff for distributed solar systems for self-consumption that include a storage component.[33] In addition, countries launched **tenders and auctions** for grid-scale storage. Australia's state energy ministers agreed to offer tenders for renewable energy and storage at the federal level.[34] France enacted specifications for its energy storage tender mechanism, and Germany held innovative auctions that allocated 403 megawatts (MW) for solar-plus-storage projects on lands with dual use.[35]

Energy storage policies take different forms globally.[36] (→ *See Figure 2.*) In Asia, India updated its Renewable Purchase Obligation to include an energy storage obligation, and the country's national budget for 2023-2024 includes provisions for funding 4 GW of storage.[37] China's state economic planner and state energy regulator published a roadmap for the energy storage sector during the period of the 14th Five-Year Plan (2021-2025), aiming for large-scale and market-oriented development to support low-carbon and reliable energy needs.[38] The Philippines is drafting new regulations to support increasing the country's storage capacity.[39]

In Europe, the EU's Net Zero Industry Act proposal includes energy storage in the definition of net zero technologies.[40] Romania allocated more than EUR 100 million (USD 109 million) in 2022 for energy storage in the industrial and commercial sectors, and in 2023 the country published new technical regulations for energy storage.[41] Türkiye published new rules to allow energy storage facilities to operate with unlicenced power plants.[42] In Latin America, Chile passed a major energy storage bill to manage grid congestion, allowing for the integration and remuneration of stand-alone storage systems.[43]

By the end of 2022,
11 national
and sub-national
jurisdictions had targets
for energy storage.

FIGURE 2.
Policies Supporting Renewable Energy Storage at the National and Sub-national Level, 2022



Source: See endnote 36 for this module.

At the sub-national level, as of March 2023, 10 US states (California, Connecticut, Illinois, Maine, Massachusetts, Nevada, New Jersey, New York, Oregon and Virginia) had adopted utility procurement targets for energy storage capacity.[44] In addition, the state of New Mexico announced a target for 7 GW of storage by 2034, and Maryland is targeting 3 GW by 2033.[45] In some cases, the phase-down of net metering policies at the national and sub-national levels (such as in California) is aimed at incentivising homeowners to invest in home battery systems.[46] In Canada, the province of Nova Scotia amended its Electricity Act to include competitive procurements for energy storage capacity, with the ability for direct government contracting.[47] Queensland, Australia is launching a Neighbourhood Battery Programme to support community storage solutions.[48]

Pumped storage is a reliable and flexible energy storage solution that balances supply and demand on the grid. China's 14th Five-Year Plan includes a target for 270 GW of pumped storage capacity, which the country aims to achieve through "the Double Two Hundred project", whereby 200 cities and counties will build 200 pumped storage systems.[49] By 2025, China aims to have 60 GW of operational pumped storage and to start construction on more than 200 additional plants, with a combined capacity of 270 GW.[50] In 2023, Greece proposed raising its pumped storage capacity from 1.1 GW to 2.5 GW, and India issued new pumped storage guidelines and added an 18 GW target.[51] At the sub-national level, Queensland, Australia included in its AUD 62 billion (USD 39.4 billion) energy and jobs plan two pumped storage facilities totalling 5 GW, equal to half of the region's peak power demand.[52]

Grid expansions are crucial for increased electrification and renewable energy uptake. Efficient integration of renewables requires investments in grid expansion and modernisation as well as regional interconnections, pushed by targeted policy measures and regulations.[53] In 2022, following passage of the Inflation Reduction Act, the US Federal Energy Regulatory Commission issued policies and regulations on transmission and distribution, including measures to accelerate permitting and licencing for solar PV and wind power projects.[54] The US Department of Energy also launched the Building a Better Grid Initiative to upgrade high-voltage transmission lines, with a budget of USD 20 million.[55] In addition, the Inflation Reduction Act allocates USD 100 million to study the feasibility of inter-regional and offshore electricity transmission networks.[56]

The United Arab Emirates enacted a law allowing grid connection for distributed renewable generation, including individual systems, in an effort to diversify its energy mix and expand the grid.[57] In Australia, the energy market operator published the 2022

Integrated System Plan to inform the infrastructure needs of a grid with increased shares of variable renewable generation; the government is providing AUD 20 billion (USD 12.7 billion) in low-cost finance to expand and modernise the grid and is developing a Capacity Investment Scheme to underwrite dispatchable capacity to ensure reliability in the rapidly changing electricity market.[58]

Regional interconnections and market integration are essential to increase grid reliability and security and quality of supply. The EU has an interconnection target of 15% by 2030, which mandates that countries have in place electricity cables that allow for at least 15% of the electricity produced to be transported to neighbouring countries.[59] As of 2022, at least 16 EU member states had reached the target or were on track to reach it by 2030.[60] In early 2023, the EU also published proposals on the design of its internal electricity market for better energy security.[61] At the 2022 United Nations Climate Conference in Egypt, five countries – France, Germany, Morocco, Portugal and Spain – launched the Sustainable Electricity Trade Roadmap to boost regional electricity market integration.[62]

In the United States, New York City announced plans to source electricity from 1.25 GW worth of existing hydropower projects in Canada.[63] The state of New York is investing USD 4.5 billion in the Champlain Hudson Power Express, which would supply 20% of New York City's electricity demand, offsetting oil and gas peaker plants.[64]

Policies for electric vehicle **charging infrastructure** received increased attention in 2022. The United States announced new standards for a National Electric Vehicle Charging Network that includes the use of renewables as an electricity source.[65] The EU reached a provisional agreement to install charging stations at least every 60 kilometres along the region's main highways by 2026, higher-powered chargers for trucks and buses at least every 120 kilometres by 2028, and hydrogen refuelling stations at least every 200 kilometres by 2031.[66]

INVESTMENT

Investment in energy storage[i] worldwide reached a record high of USD 15.7 billion in 2022, up 46% from 2021.[67] Corporate funding for energy storage was up 55% from 2021.[68] The leading categories were grid-scale storage and lithium-ion batteries.[69] China and the United States led in energy storage investment, although other markets – such as Australia, Europe, Japan and the Republic of Korea – also gained traction.[70]

In **China**, the release of the 14th Five-Year Plan for the Development of New Energy Storage Technologies in March 2022 called for government and private entities to build additional storage capacity, paving the way for more targeted investment.[71] In the **United States**, the Bipartisan Infrastructure Law of 2021 strongly supported investment in the battery supply chain, and the Inflation Reduction Act of 2022 led to more than USD 80 billion in new investments[ii].[72] **Japan** allocated JPY 13 billion (USD 100 million) in subsidies for stand-alone battery systems in 2022 and was reforming its regulations for battery energy storage systems in 2023, which will further support investment.[73] In **Australia**, the government announced funding of USD 118 million in 2022 for eight large-scale battery storage projects.[74] Tenders for energy storage projects in the country were scheduled to begin in 2023, supporting ongoing investment in the technology.[75]

In developing countries, international development banks actively financed several energy storage projects in 2022, often coupled with renewable energy installations.[76] The US International Development Corporation provided a loan of USD 25 million for a solar PV plus storage project in Malawi.[77] The Inter-American Development Bank and the Norwegian Agency for Development Cooperation invested USD 83.3 million in eight solar PV projects in Guyana with co-located energy storage.[78]

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[i] These data include stationary storage projects (large- and small-scale) but do not include pumped hydropower, compressed air or hydrogen. The majority are battery projects. The data cover capital spent on deployment and largely exclude capital invested in companies, research and development, and manufacturing.

[ii] These investment numbers include recycling, materials separation and processing, and component manufacturing, which are typically excluded from storage investment figures elsewhere.

Although no global datasets are available for investment in pumped hydropower storage, more than 100 projects were in the pipeline worldwide as of 2022.[79] Investments in individual projects included USD 2.5 billion for the Seminoe Project in the US state of Wyoming, USD 1.45 billion (CNY 10 billion) for the Zhejiang Jinyun Project in China and USD 1.7 billion for the Gouvaes Project in Portugal.[80]

Investment in power grid infrastructure totalled an estimated USD 274 billion in 2022, most of it in the United States, China and Europe.[81] In the United States, only around 30% of the investment was devoted to grid expansion; a growing share was used to replace and upgrade equipment and to strengthen structures against weather-related damages (such as installing better power poles to withstand high winds).[82] China has budgeted more than CNY 500 billion (USD 72.4 billion) for ultra-high-voltage projects, upgrading the distribution network and digitalising grids.[83] In Europe, investment has focused on connecting offshore wind farms, modernising ageing infrastructure and digitalising grids to allow demand-side load management, electric vehicle charging and electrification of industry.[84]

Other countries also made relevant power grid infrastructure investment announcements in 2022. In Australia, AUD 20 billion (USD 13.6 billion) was allocated for the Rewiring the Nation network overhaul, aimed at upgrading and extending transmission lines to allow for greater integration of renewables and to enable energy storage to play a wider role in the electricity market.[85] India announced USD 29.6 billion to build additional transmission to connect renewables.[86] Investment in electricity networks in the developing world has been impeded by the weak financial situation of some distribution companies, the lack of adequate investment frameworks (such as performance-based regulation), the lack of least-cost system plans, and high operational and commercial losses.[87]

Global investment in grid infrastructure reached

274 USD billion

in 2022.

MARKET DEVELOPMENTS

Pumped storage continues to account for the largest portion of global energy storage capacity by far. In 2022, global pumped storage capacity increased by 10.5 GW for a total of 175 GW.[88] **Utility-scale battery** capacity has grown much faster but from a relatively small base.[89] (→ *See Figure 3.*)

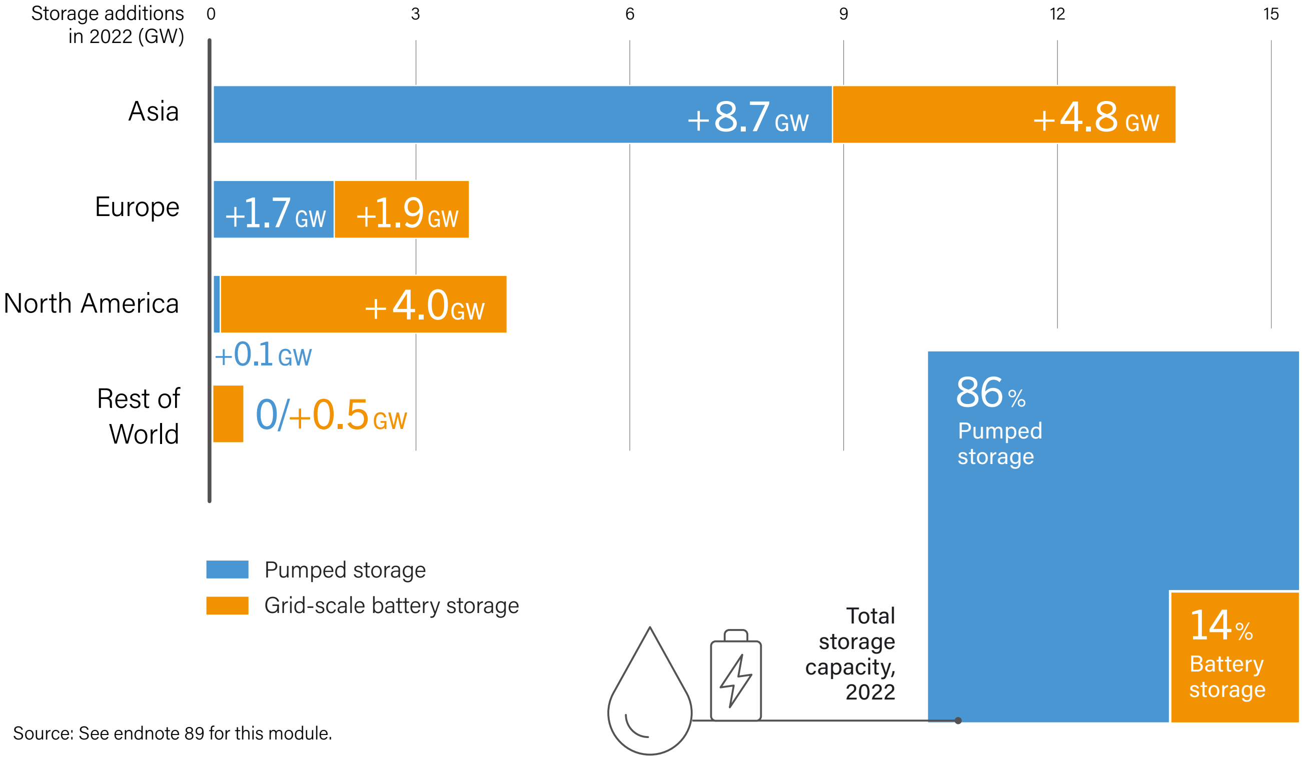
Pumped storage capacity is concentrated mainly in **China**, with 26% of the global capacity.[90] In 2022, China accounted for 82% of the newly added capacity, leading in pumped storage additions for the 10th year in a row.[91] The Jinzhai pumped storage plant in Anhui Province was completed in January 2023, connecting more than 1.2 GW and contributing to the total of 8.8 GW of pumped storage added to the Chinese grid in January 2023.[92] Construction began on the USD 3 billion Fengning plant, which is expected to store up to 40 gigawatt-hours (GWh) of electricity and will use 12 reversible turbines to produce energy in high demand periods, pumping water to the upper reservoir at times of low demand.[93]

In **Europe**, two major pumped storage facilities came online in 2022. In Portugal, the Tâmega Gigabattery, capable of storing 40 GWh, was inaugurated in July, and the first of four 220 MW pump turbines at the Gouvães hydropower plant was added to the Tâmega hydropower complex, where the Gouvães, Daivões and Alto Tâmega reservoirs are poised to generate an estimated 1.8 TWh per year when completed in 2024.[94] In Switzerland, the 14-year Nant de Drance project came online at a cost of USD 2.15 billion, with a reservoir capable of storing 20 GWh that will feed a series of six turbines with a total capacity of 900 MW.[95]

In the **United States**, two projects with a combined pumped storage capacity of up to 17 GWh were submitted for the final licencing phase, joining only six other projects that have reached that phase in the last 20 years.[96]

Total **utility-scale battery** capacity increased by around 67% in 2022, adding 11 GW to reach 28 GW in operation.[97] In the United States, installed grid-scale battery storage reached around 9 GW, with nearly half of this (4 GW) installed just in 2022.[98] In Europe,

FIGURE 3.
Capacity Additions of Pumped Storage and Utility-Scale Battery Storage, by Region, and Total Storage Capacity, 2022



Source: See endnote 89 for this module.

including the United Kingdom, 1.9 GW was installed in 2022, bringing the total capacity to 4.5 GW.[99] In China, an estimated 4.8 GW of utility-scale battery storage capacity was added, for a total installed capacity of 8.5 GW.[100]

With regard to **regional interconnections**, in August 2022 the transmission system operator TenneT agreed to 14 offshore grid connection contracts in the German and Dutch areas of the North Sea.[101] The contracts totalled around EUR 30 billion (USD 32.9 billion) and are expected to result in a transmission capacity of 28 GW of offshore wind power.[102] This represents Europe's largest-ever grid infrastructure contracting package and was driven mainly by concerns about the security of supply and by the transition to renewable electricity.[103]

In 2022, **India** and the **Maldives** signed a memorandum of understanding to establish a transmission interconnection for renewable energy.[104] **Egypt** and **Saudi Arabia** similarly signed a memorandum of understanding and subsequent contracts to establish an electricity interconnection line between the countries.[105] The EU's Agency for the Cooperation of Energy Regulators published bidding zone configurations for transmission system operators to exchange energy without capacity allocation.[106]

Sector coupling requires precise co-ordination, which can be achieved through digitalisation. Sector coupling can benefit from smart grids, smart network infrastructure development, and the development of "digital twins" as a data-based testing site for energy management and sector coupling.[107] Projects continue to be developed: Allianz provided EUR 25 million (USD 27.8 million) for a green hydrogen and power-to-gas project in **Finland**.[108] In **Denmark**, a 6 MW power-to-hydrogen prototype unit has been deployed to supply extra thermal energy to a district heating system.[109]

With regard to **energy storage optimisation**, Pacific Gas and Electric (PG&E) in the US state of California uses artificial intelligence, advanced price forecasting, portfolio optimisation and market bidding algorithms to ensure that the electric system is responding optimally to wholesale market reliability needs.[110] In 2021, California's Independent System Operator (CAISO) implemented a trading platform powered by artificial intelligence to provide optimisation and market bidding services to the 182.5 MW (730 MWh) battery storage system in Moss Landing.[111] The platform provides asset and portfolio managers with updated price forecasts and optimised bids every hour, allowing PG&E to maximise the value of the asset for its customers, improve grid reliability and efficiency, and support California's transition to a more stable and resilient electric grid.[112]

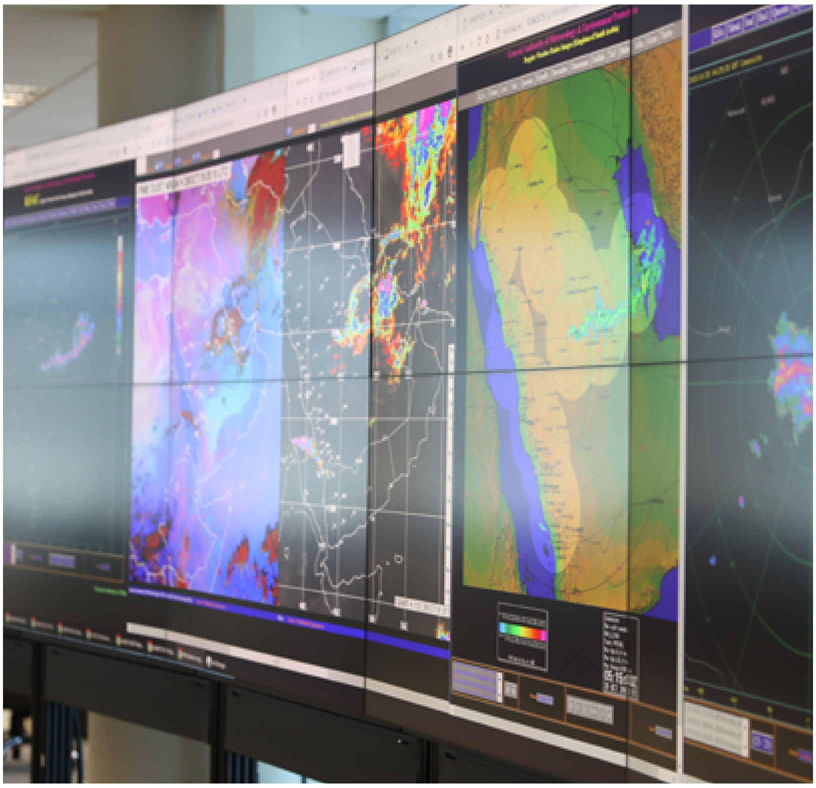
Data analytics in **weather forecasting** also helps power producers optimise their operations, reduce grid balancing costs, and improve the integration of wind and solar energy into the grid. In 2019, several states in India issued prediction requirements obligating operators of wind and solar farms to provide the respective grid operator with scheduling details for power generation, either through engagement with a qualified co-ordination agency or by fulfilling the prediction requirements themselves.[113] In case of imprecise predictions, power producers may incur fees due to outages.

In 2022, scientists in Spain developed a new methodology for long-term prediction that focuses on the atmospheric circulation patterns on a planetary scale.[114] In the EU, the Destination Earth initiative (Use Case Energy Systems) provides tools and guidance to support grid operators with system modelling and grid planning by improving the accuracy and reliability of clouds and storm data and analysis.[115] Those forecasting solutions use advanced models, local weather data and historical performance data to deliver high-quality predictions, contributing to greater efficiency, reliability and economic viability of projects.

During 2019-2022, the Smart4RES project (funded by the EU's Horizon 2020 research and innovation programme) focused on research and development and the validation of a next generation of tools for modelling and forecasting energy production from variable renewable energy, as well as on decision making within different power system and electricity markets.[116] The project, which concludes in 2023, has proposed tools to ensure at least a 15% increase in the forecasting performance of variable renewables.[117] It also defines requirements for forecasting technologies to enable near-100% penetration of renewables by 2030 and beyond, introducing new data-driven optimisation and decision-making tools to enable the large-scale penetration of renewables into the electricity market and the provision of system services towards transmission and distribution system operators.[118]

In Japan, customer-centric **demand-side management** aims to optimise the operation of 74 GW of installed solar energy that drives the common "duck curve[i]" of low mid-day prices and steep ramping rates in the evening.[119] Japan's Agency for Natural Resources and Energy has outlined a strategic plan that focuses heavily on demand-side measures, with new balancing and flexibility products being developed starrng in 2022. These include: 1) a capacity mechanism; 2) reserve product replacement reserves for feed-in tariffs opened to demand aggregators, with day-ahead bidding and availability payments; and 3) a suite of faster operarng services providing frequency response, requiring on-site reaction to the changing frequency.[120]

A **virtual power plant (VPP)** is a cloud-based network that consists primarily of distributed energy resources – such as solar panels, wind turbines and energy storage systems – that are aggregated and co-ordinated to operate as a single entity[ii]. VPPs can be controlled and optimised using advanced software algorithms, which enable them to provide grid services, such as frequency regulation and voltage control. This can help stabilise the grid and improve the integration of renewable sources. VPPs can: 1) ensure enhanced grid reliability by pooling resources, helping to stabilise the grid during periods of peak demand or during fluctuations in renewables, improving the overall reliability of the power system; 2) ensure optimal use of distributed resources, by co-ordinating their operation according to grid requirements and market conditions; and 3) reduce investment in traditional centralised power plants, by harnessing the combined capacity of smaller, decentralised, distributed energy resources.



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[i] The term was first used in 2012 and was coined by the California Independent System Operator in the United States.

[ii] VPPs can also (less commonly) aggregate other, non-distributed energy resources.

Many countries worldwide saw rising interest in VPPs in 2022, and the market value globally reached USD 3.36 billion.[121] (→ *See Table 1.*) One of the largest VPP operators in Europe, Next Kraftwerke, has more than 15,000 aggregated units across eight countries, with a network capacity of roughly 13 GW and an annual trade volume of more than 15 TWh.[122] Given its innovative and successful business model, the company was acquired in 2021 by Shell.[123] BP was the first to jump on this trend in 2021 when it acquired Blueprint Power, a US-based VPP operator.[124] Along with the acquisition, in early 2023 Lighthouse bp, a subsidiary of BP, began a solar plant operation in the US state of Indiana, supported by a virtual power purchase agreement.[125]

China has established pilot projects to build VPPs in locations such as Hebei, Shandong, Shanghai and Shanxito to distribute electricity more efficiently. The newly launched VPP in Shenzhen can pull together a capacity of 870 MW, which is planned to increase to 10 GW by 2025.[126] In Japan, Tesla has been installing its Powerwall batteries in homes on Miyako-jima island since 2021, with more than 300 installed to form the country's largest commercial VPP.[127] Dubai Electricity and Water Authority in the United Arab Emirates is now using a VPP, the first of its kind in the Middle East, to enhance its smart grid integration between different energy sources.[128]

In Greece, Protergia, the power and gas unit of the Greek company Mytilineos, together with the German firm emsys VPP, officially inaugurated the country's first VPP in 2022.[129] Equipped with the complete software-as-a-service solution for aggregators, Protergia has digitised its own solar and wind power portfolio, as well as those of third parties, to monitor, forecast, remote-control and trade their variable electricity production in real time. The facilities will be enabled to participate in the market as balancing service providers on their own or through a renewable energy aggregator, which, with proper management, will revitalise existing revenue streams.[130]

In the United States, the Puerto Rico Electric Power Authority (PREPA) selected Sunrun in 2022 to deploy a 17 MW solar-plus-storage VPP network, marking the first large-scale distributed storage project on the island.[131] In Puerto Rico, having experienced many hurricanes such as Maria in 2017, a VPP network can stabilise the island's power grid by connecting more than 7,000 Sunrun residential solar-plus-storage systems.[132]

Microgrids represent a shift in electricity generation, distribution, and consumption, offering economic benefits, enhanced reliability, resilience, and sustainability by operating as self-contained power systems that can connect to or operate independently of the main grid, optimising the performance of renewable and conventional energy assets, particularly in rural and off-grid areas.[133] (→ *See Sidebar 2.*) Microgrids can demonstrate resilience in extreme weather events and showcase how renewables can create sustainable and resilient communities in the face of climate change and natural disasters.[134] (→ *See Snapshot: United States.*)

Table 1.
Networked Capacity of Selected VPP Operators Worldwide, as of Early 2023

VPP operator (Location of headquarters)	Total network capacity (MW)
Centrica (United Kingdom)	15.400
Statkraft (Norway)	14.000
Next Kraftwerke (Germany)	11.200
Enel X (Italy)	8.500
Autogrid (United States)	6.000
Flextricity (United Kingdom)	800
OhmConnect (United States)	550
Tesla (United States)	300
AGL (Australia)	215

Source: See endnote 121 for this module.

SIDEBAR 2. Microgrids

Microgrid (or minigrid[i]) systems represent a major shift in the way electricity is generated, distributed and consumed. Microgrids are small- to medium-scale, self-contained power systems that can operate independently of the main power grid (in islanded mode) or in parallel with it, depending on the needs of the local community or facility.

Microgrids are an increasingly popular way to optimise the performance of both renewable and conventional energy assets, particularly in rural areas and areas with no access to a unified power grid. A key distinction between microgrid systems and VPPs is that microgrids are physical, on-site power systems that generate and distribute electricity within specific geographic areas, whereas VPPs are software-based platforms that aggregate multiple distributed energy resources to provide grid services.

The main value propositions of microgrids relate to their economics and energy efficiency, reliability, resilience and sustainability. Microgrids can offer cost savings by optimising capital and operational expenditures through efficient load and energy storage management, as well as effective control of distributed energy resources, leading to reduced energy costs and increased return on investment.

Microgrids enhance system reliability and resilience by offering network synchronisation, black-start capabilities and enhanced SCADA (Supervisory Control and Data Acquisition) functionality. Network synchronisation allows microgrids to seamlessly connect and disconnect from the main grid, maintaining stability and minimising disruptions. Black-start capabilities enable microgrids to restore power independently during grid outages, ensuring continuous power supply to critical loads. Enhanced SCADA functionality provides advanced monitoring and control of the microgrid, ensuring optimal performance and rapid response to potential issues, further improving the overall reliability and resilience of the power system.

Some microgrids can contribute to long-term sustainability through advanced functionalities such as generation and load forecasting, as well as state estimators to assess dynamic grid constraints. Using these functional specifications, microgrids can efficiently plan and manage their resources, reducing the reliance on non-renewable energy sources and promoting the use of renewable energy. Dynamic grid constraint consideration through state estimator functions helps microgrids adapt to changing grid conditions, ensuring that distributed energy resources are optimally used while maintaining grid stability and fostering the transition to a more resilient renewable energy-based system.

[i] The term “minigrid” is more commonly used in developing countries where energy access in remote areas is the primary value proposition.

Source: See endnote 133 for this module.

SNAPSHOT

UNITED STATES

Microgrids for Resilience Against Natural Disasters

Babcock Ranch in South Florida is a 100% solar community, calling itself "America's first solar-powered town". The local solar array, made up of 700,000 individual panels, can generate more electricity than is used in the 2,000-home neighbourhood, in a state where most power is generated by burning fossil gas. In 2022, when Hurricane Ian battered Florida's eastern coast, the community did not lose power or Internet connectivity, showcasing its robust design and ability to withstand extreme weather events. The town's infrastructure includes a network of lakes to mitigate flooding, energy-efficient buildings, and a microgrid system that enables it to function independently from the main grid.

Babcock Ranch serves as an example of how solar power, coupled with thoughtful planning and advanced technology, can create sustainable, resilient communities that can thrive in the face of climate change and natural disasters. To benefit from the inherent resiliency of distributed power and the microgrid-intelligent controllers, the solar panels must first survive a severe storm event, whether on the ground or attached to roofs. Encased in glass, the thin and technologically complicated solar PV modules would appear to be a prime target for hurricane-force destruction, but solar panels are surprisingly robust. Solar installers often take extra precautions when installing systems in hurricane-prone areas, designing them specifically to withstand the highest possible hurricane-force winds and making sure the solar panels will stay safe.

Source: See endnote 134 for this module.

CHALLENGES AND OPPORTUNITIES

for the Uptake of Renewables in Energy Systems & Infrastructure

CHALLENGES

- → The variable nature of solar and wind power, which can fluctuate based on weather patterns and other variables, could affect system stability, making it more difficult to balance supply and demand.
- → Curtailment of variable renewable energy sources is expected to increase as their share in electricity systems increases.
- → Integration of variable renewables in electric grids requires careful planning and co-ordination among different stakeholders.

OPPORTUNITIES

- → Grid infrastructure, storage, digitalisation, planning and accelerated permitting are key to realising the full integration of renewables in the power system.
- → Electrification, sector coupling, thermal storage and demand side-management can optimise the use of renewables in the energy system.
- → The number of countries with high shares of variable renewables in the electricity system is increasing.

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RENEWABLES NOW

RENEWABLES 2023
GLOBAL STATUS REPORT

RENEWABLES IN ENERGY SYSTEMS & INFRASTRUCTURE

ISBN 978-3-948393-09-0

REN21 Secretariat
c/o UN Environment Programme
1 rue Miollis
Building VII
75015 Paris
France

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2023
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