

SEPTEMBER 2025

Understanding the modern electrical grid

Challenges and investment opportunities





Introduction

The electricity grid is at the heart of the clean energy transition and is undergoing one of the most significant transformations in its history. Understanding the modern electrical grid is no easy task, but it is a necessary one, as the grid plays a critical role in economic growth, energy security and decarbonisation. With the rapid growth of solar, wind power and electric vehicles (EVs) investing in larger and smarter infrastructure networks will be critical.¹ Renewable capacity must be integrated into power systems more quickly and efficiently, while grid expansions and permitting times need to keep pace. A new energy system should be built to last: this means prioritising security, resilience and flexibility.²

Energy security remains at the top of the agenda, as geopolitical tensions, trade disruptions and rising economic nationalism influences national energy strategies. Countries are looking to secure supply, reduce external dependencies and control prices,³ amid fear that Russia's continued war in Ukraine and conflict in the Middle East could lead to further disruption within energy markets. There is also an increasing need for digital security, to make sure power systems are as safe as they can be from cyberattacks.⁴

Alongside security concerns, the rise of electricity demand and more variable generation increase the need for flexibility in power systems. Many systems are vulnerable to an increase in extreme weather events and need investment to strengthen their resilience.⁵ Extreme volatility in energy markets during the global energy crisis also highlighted the importance of maintaining a reliable supply

of power. Expanded, modernised and cybersecure transmission and distribution grids are critical to electricity security as we electrify and decarbonise, and as the share of solar PV and wind in electricity generation rises.⁶

There are many changes on the horizon for the global electricity system. The Iberian Peninsula blackout in April 2025 exposed further critical vulnerabilities, but also opened a window of opportunity for innovation and investment, particularly from the private sector. Rising EV demand and battery utilisation (from both Battery Energy Storage Systems (BESS) and EVs as a distributed BESS) can help to strengthen the grid.

This paper aims to examine how the grid works, the impact of renewables, the evolution of grid technology and how investors can participate in its modernisation.

“Countries are looking to secure supply, reduce external dependencies and control prices.”

How the electrical grid works

Generation, transmission, distribution

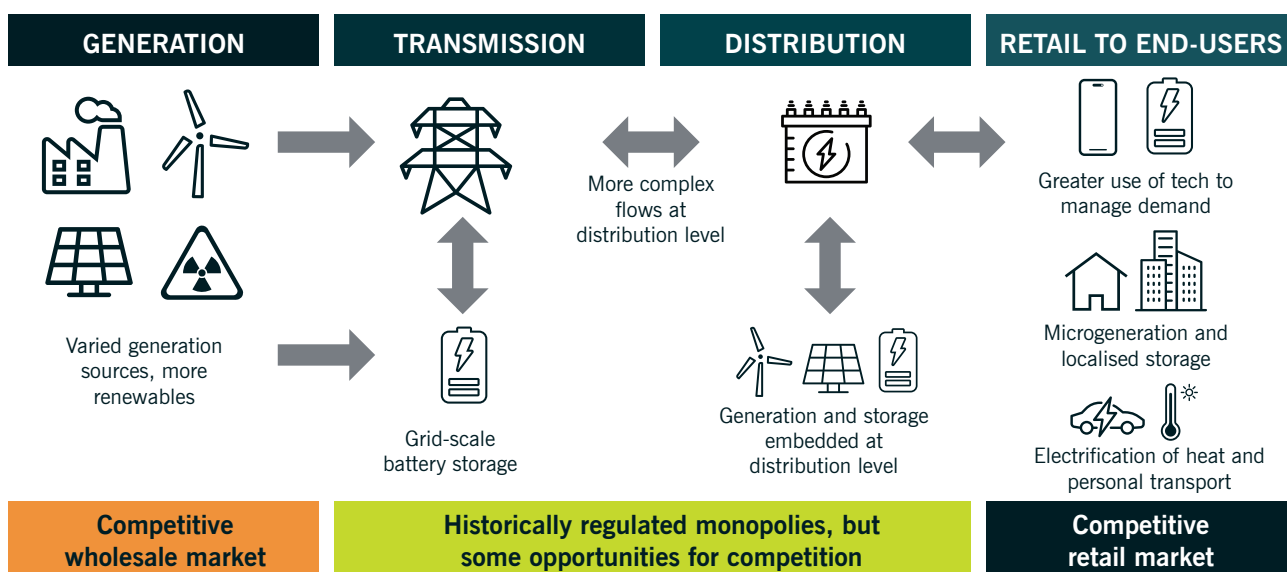
Electricity is generated from diverse energy sources and technologies. The three major categories are fossil fuels (coal, natural gas and petroleum), nuclear energy and renewable energy. Historically, most electricity was generated with steam turbines that used fossil fuels, nuclear, biomass, geothermal or solar thermal energy. Other major electricity generation technologies include gas turbines, hydro turbines, wind turbines and solar PV.⁷

Transmission networks carry the electricity generated at power plants to substations, through overhead transmission lines and submarine cables, across long distances, at high voltage.⁸ Transformers aid this journey, changing the voltage of electricity in a conductor or power line; they increase (step up) or reduce (step down) voltages as electricity moves from power plants to where it is needed. This is because higher voltage electricity is more efficient and less expensive for long distance electricity transmission, while lower voltage electricity is safer for use in homes and businesses.⁹ Distribution networks then transport

electricity from transmission networks to end-users. These include smaller pylons and underground cables carrying lower voltage lines.¹⁰

This traditional system is evolving rapidly. Many transmission and distribution systems were designed decades ago and are not well-suited for today's decentralised renewable energy sources.¹¹ We are now moving from a centralised, top-down system of electricity generation to a more decentralised structure, where transmission and distribution are playing a larger role.¹² This is key for the changes that are required on the grid network.

By harnessing distributed resources like solar, wind and battery storage, decentralised grids offer a cleaner, more resilient alternative to traditional centralised systems. Historically, energy generation has relied on a hub-and-spoke model, where electricity is generated by a few entities at large, centralised power plants and distributed over long distances. While this model provides economies of scale, it has many challenges, including inefficiencies, vulnerabilities to disruptions, and a limited capacity to integrate renewable energy sources.¹³





In contrast, the decentralised energy grid comprises smaller, more widely spread power generators that feed into the distribution grid. Energy is bidirectional, allowing end consumers to produce and sell excess energy back to the grid. This promotes energy resilience and reduces transmission losses, but requires significant infrastructure investment, efficient management, conversion and storage of electrical energy, as well as coordination among small generators.¹⁴

Supply and demand

To ensure a steady supply of electricity, grid operators call on electric power plants to produce and supply the right amount of electricity to the grid to meet and balance electricity demand. Most power plants do not generate electricity at their full capacities and most generating units vary their output. Operating strategies for generators can be grouped into several major types:¹⁵

Base-load service normally supplies all or part of the minimum, or base, demand (load) on a system. Base-load generating units tend to run nearly continuously. Nuclear power plants, geothermal plants, biomass-fired plants and many large hydro generators are often operated as base-load resources because of their low fuel costs (and in the case of nuclear, they do not like to be ramped up and down).

Intermediate-load service makes up the largest generating sector and provides load responsive operation. Many natural gas-fired combined-cycle

applications operate as intermediate resources because of their ability to ramp up and down quickly, which allows them to follow changes in demand.

Peak-load service helps to meet electricity demand when demand is at its highest. Peaking units can serve relatively short demand periods, often a few hours a day. Daily peaking units are mostly natural gas- or petroleum-fuelled internal combustion engine or combustion turbine generators. These generators are usually relatively inefficient and costly to operate. Other peaking units may operate in a seasonal capacity, operating for several days or weeks to support the grid during extreme hot or cold weather conditions.

Intermittent renewable resource generators include wind and solar energy power plants, as well as hydro. When these generators are operating, they often reduce the amount of electricity required from other generators to supply the grid.

Energy storage systems (ESS) provide a variety of services to support electric power grids. In some cases, energy storage may be paired or co-located with other generation resources to improve the economic efficiency of one or both systems.

Distributed generators refer to smaller scale technologies located close to the point where the electricity will be consumed, rather than at large, centralised power plants. These systems typically connect to the lower-voltage distribution network, or directly to a consumer's premises, rather than to the high-voltage transmission grid.

Ancillary services

Ancillary services play a crucial role in maintaining grid stability, balancing supply and demand, and ensuring the reliable supply of electricity. They enable the efficient and secure operation of the power grid and include frequency regulation, voltage support and spinning reserve. The variability and intermittency of renewable energy sources such as wind and solar power need a more sophisticated and responsive grid management system, which ancillary services can provide. The increasing penetration of renewable energy sources is driving innovation in the sector, with new technologies and market mechanisms being developed.¹⁶ Solutions for maintaining a balanced grid system (and therefore vital ancillary services) include:

FREQUENCY REGULATION

Grid frequency is a measure of the balance between electricity supply and demand, and any deviations from the nominal frequency can indicate a mismatch between the two. Frequency regulation ensures that the grid frequency remains within acceptable limits. A stable grid frequency is essential for the reliable operation of the power grid, as it ensures that generators and loads operate in synchrony. Frequency deviations can lead to equipment damage, reduced efficiency and even grid instability.¹⁷

VOLTAGE SUPPORT

A lack of voltage control appears to be the cause of the Iberian blackout.¹⁸ Operators need to make sure voltage stays within acceptable limits and voltage support ensures this. Voltage support involves adjusting the reactive power output of generators or other devices to maintain the grid voltage within a narrow range. The management of reactive power is essential for maintaining grid voltage, as it enables the grid to respond to changes in demand or supply. Reactive power management involves the use of advanced control systems and devices such as capacitor banks and synchronous condensers.¹⁹

SPINNING RESERVE

Spinning reserve involves maintaining a portion of the grid's generating capacity in a state of readiness to respond to changes in demand or supply. Spinning reserve is typically provided by generators that are online and operating at less than full capacity, or by BESS which can respond rapidly. It provides a rapid response to changes in demand or supply, ensuring that the grid remains stable and reliable, and is essential for managing the variability and uncertainty associated with renewable energy sources.²⁰

BLACK START CAPABILITY

This allows operators to restore the electrical system region by region after a total or partial shutdown of the transmission system. Isolated power stations are started individually and gradually reconnected to each other, bringing the whole system back up in a stable way.²¹

INERTIAL BALANCE

Inertia can help with frequency fluctuations.²² In a power grid, inertia is the kinetic energy derived from hundreds or thousands of spinning generators that are synchronised, meaning they are all rotating at the same frequency. Inertia gives the system operator a chance to respond to power plant failures (contingencies). This is because inertia resists changes in frequency, giving other systems time to respond and to rebalance supply and demand.²³

Impact of renewable energy integration



In 2024, global renewable power capacity increased 18%, adding a record-breaking 741 GW. This was largely driven by solar PV, which contributed 602 GW (81% of the total capacity increase), while wind energy provided 117 GW. In 2024, 33 countries generated over half of their electricity from renewable sources, and 15 countries successfully integrated more than 30% of variable renewable electricity from wind and solar into their electricity mix.²⁴

There are bottlenecks within the current top-down grid infrastructure. As we move to more renewable energy, we need to rework the design of the grid system to prevent connection queues. The grid needs support at intermediate points to allow new generation sources to connect and transport their power. With the right support, transmission networks can become more flexible, making it easier to maintain balance and to keep voltage fluctuations within limits. Grid support services are essential for providing solutions and there are many technical upgrades needed, including technologies relating to frequency regulation, voltage support, inertia protection and black start capability.²⁵

Developers also have the challenge of grid connection queues. As of mid-2024, an estimated 1,650 GW of renewable energy capacity in advanced development stages was awaiting grid connection globally, up 150 GW from 2023.²⁶ The lack of grid availability is, in turn,

hindering growth in renewables-based generation in some markets.²⁷

The good news is that power system infrastructure is already evolving to support electrification and the integration of more distributed and variable renewable electricity into the world's grids. In 2024, in addition to reinforcing and expanding transmission networks and interconnections, regulators and system operators increasingly looked at flexibility measures. This included considering energy storage, demand response and the use of digital technologies to ensure grid stability and reliable supply.²⁸

Over the last decade, the number of intermittent renewable resource generators (that only produce electricity when wind and solar energy is available) has grown to a relatively large share of the industry. The IEA expects global annual renewable capacity additions to rise from 666 GW in 2024 to almost 935 GW in 2030, with solar PV and wind forecast to account for 95%.²⁹ Generator operating strategies will likely shift. Units that used to operate in base-load might now follow an intermediate strategy. Other units in both the base-load and intermediate categories that have operational flexibility might vary their output over a wide range to minimise the costs of startups and shutdowns.³⁰



Technological changes in the grid

Blackout in Spain and Portugal

In April 2025, Spain and Portugal suffered an enormous electricity blackout, affecting 55 million people and lasting over 12 hours in some areas. Many blamed the intermittent nature of renewables, as 80% of electricity on the grid was from solar and wind when the blackout hit, but this does not appear to be the cause.³¹ The blackout is thought to be the result of a lack of voltage control and an unbalanced system, alongside insufficiently rapid responses from generators.³² Rather than causing instability, renewable energy generation and other technologies such as grid-forming inverters, BESS and synchronous condensers can strengthen, support and balance the grid, delaying or removing the need for more costly grid infrastructure projects.³³

Grid-following vs grid-forming inverters

Inverters are used to convert DC into AC current needed for most household appliances, or used to produce a more uniform AC output. Grid-*following* inverters are currently the most common type of inverters used in grid-connected applications, such as renewable energy generation, energy storage and EV charging. Grid-following refers to the control strategy of an inverter-based energy source, such as solar, wind or battery, that synchronises its output with the grid voltage and frequency. These inverters track the grid angle and magnitude to inject or absorb active and reactive power. However, they rely on the grid to provide a stable voltage and frequency, and cannot operate in islanded or off-grid mode. This can cause stability and security issues for the grid, especially when there is a high penetration of renewable energy sources.³⁴

As the share of renewable energy sources increases in the grid, we need more grid-*forming* inverters

that can provide voltage and frequency support and ancillary services to the grid.³⁵ Grid-forming is an emerging technology produced by leading inverter manufacturers. Grid-forming refers to the ability of an inverter-based energy source, such as solar, wind or battery, to provide voltage and frequency support to the grid, especially during disturbances or outages. These inverters can operate independently or in coordination with other sources, and can help restore the grid after a blackout. Grid-forming inverters strengthen grid performance, allowing voltage control and virtual inertia.³⁶ This is a key technology for integrating more renewable energy into the grid and ensuring its reliability and stability.³⁷

Energy storage

Energy storage systems are vital for the decentralised energy grid. They enable the capture and storage of surplus electricity during low demand, allowing it to be released during peak periods. This prevents grid overloads and ensures a reliable power supply.³⁸ There are a variety of ESS, including batteries, pumped storage, thermal storage and hydrogen. All of these can help stabilise power grids, especially in the context of the increased penetration of variable renewables.³⁹

Energy storage can help balance electricity supply and demand by the second, minute or hour. Fast response (ramping) ESS can provide ancillary services for electric power grids to help maintain electric grid frequency on a second-to-second basis. Energy storage can also improve power quality and reliability. These are important attributes of grid electricity because momentary spikes, surges, sags or outages can harm equipment powered by electricity. Energy storage can provide greater and more effective use of intermittent solar and wind. Pairing or co-locating an on-grid ESS with wind and solar energy power plants can allow those power plants to respond to supply requests (dispatch calls) from electric grid



operators when direct generation from solar and wind is unavailable or limited.⁴⁰

The deployment of battery energy storage systems hit record levels in 2024, driven by falling prices and the growing recognition that storage is critical for grid reliability. An estimated 69 GW of new battery storage capacity was deployed globally during the year, bringing the total installed capacity to an estimated 150 GW. The grid-connected segment accounted for 78% of this growth.⁴¹

BESS can strengthen the grid in a variety of ways, without the need for direct grid investment, such as new, expensive substations, and power transmission and distribution lines. On the generation side, batteries can smooth fluctuations, while on the consumption side they can also relieve peak load pressure. When combined with grid-forming inverters, BESS offers: fast frequency response; voltage support; virtual inertia; and black start capability. Synchronous condensers, located at decommissioned conventional power plants, can also be combined with BESS to provide fast frequency response, voltage support and inertia.⁴²

Electric vehicles

Electric vehicle sales continued to rise in 2024, with more than 17 million units sold globally, more than one-fifth of global car sales. EV adoption is expanding beyond China (the leading market) and high-income countries, with record sales reported in emerging economies such as Brazil, India, Thailand and Turkey, and the number of charging points globally has doubled

since 2022.⁴³ EV batteries could be repurposed for storage applications. They could also support grid flexibility through smart charging, helping to optimise grid load, and through bidirectional charging, supplying power to buildings or the grid.⁴⁴

Smart technologies

Utilities are using smart grid technologies to monitor and control electricity flow in real time, reducing waste and power outages. As energy sources diversify, demand patterns become increasingly complex. AI can assist with grid management and ensure that power reaches end users cost-effectively, minimising transmission losses. Efficient energy conversion technologies are also vital for integrating renewable energy sources into the grid. As the number of inverters rises, opportunities for smarter controllers that can adapt to the state of the grid are emerging.⁴⁵

Pilot projects using Dynamic Line Rating and Advanced Power Flow Control advanced to operational deployment in 2024. These smart technologies are being integrated into utility planning and regulatory frameworks. Regulators and regional authorities (such as the U.S. Federal Energy Regulatory Commission and the U.S. state of Minnesota) have increasingly required the use of these technologies on transmission lines to improve grid efficiency. Utilities worldwide are deploying operational grid-enhancing technologies, including National Grid in the U.S. state of New York, Red Eléctrica de España (REE) in Spain, the German-Dutch transmission system operator TenneT, ISA Energia in Brasil and ISA Transelca in Colombia.⁴⁶

Regulatory landscape



Global

Grid regulation should incentivise grid operators to keep pace with the rapid changes in electricity demand and supply. This requires addressing administrative barriers, rewarding high performance and reliability, and spurring innovation. Governments need to devise long-term strategies for transmission and distribution grids, as new grid infrastructure often takes five to 15 years to plan, permit and complete, compared to one to five years for new renewables projects and less than two years for new EV charging infrastructure. Grid buildouts need secure supply chains and a skilled workforce. Governments can support the expansion of supply chains by creating strong and transparent project pipelines, and by standardising procurement and technical installations. They can also enable future flexibility by factoring interoperability into the system.⁴⁷

Barriers to grid development differ from country to country. The financial health of utilities is a central challenge in some places, including India, Indonesia and Korea, while access to finance and high cost of capital are key barriers in many emerging market and developing economies, particularly sub-Saharan Africa. Financial barriers can be addressed by improving the way grid companies are remunerated, driving targeted grid funding and increasing cost transparency. For other jurisdictions, such as Europe, the United States, Chile and Japan, the strongest barriers relate to public acceptance of new projects and the need for regulatory reform. Here, policy makers can accelerate progress on grids by improving planning, ensuring regulatory risk assessments allow for anticipatory investments and streamlining administrative processes.⁴⁸

At the November 2024 United Nations Climate Change Conference in Baku, Azerbaijan (COP 29), 65 countries signed the Global Energy Storage and Grids Pledge, committing to deploy 1,500 GW of energy storage and to develop or refurbish 25 million km of grid infrastructure by 2030. 57 countries also endorsed the Green Energy Zones and Corridors Pledge, which aims to accelerate the development of renewable energy and transmission infrastructure through international cooperation.⁴⁹ In the Net Zero Emissions Scenario, as defined by the IEA, transmission and distribution grids expand by around 2 million km each year to 2030. Around 30,000 to 50,000 km of CO₂ pipelines would be installed by the same year, together with new hydrogen infrastructure. Investment on this scale depends on expedited planning and permitting processes.⁵⁰

Technologies such as grid-forming batteries and inverters and the provision of virtual inertia are increasingly integrated in grid modernisation strategies to ensure the integration of renewables. Examples include the Grid Modernization Strategy of the U.S. Department of Energy, the Inertia Report of the Australian Energy Market Operator, the System Stability and Resilience innovation priority of Great Britain's National Energy System Operator (NESO), the Roadmap for an Accelerated Energy Transition of Chile's power coordinator, the recommendations of the Grid Controller of India, and Eskom's (South Africa) inertia estimation tool in collaboration with the Global PST Consortium.⁵¹



Europe

The EU has adopted a number of new laws to ensure the EU electricity market is better connected and able to integrate renewable energy, more protected against blackouts, more market-based and more consumer-oriented. The new rules include the revised electricity market regulation, the revised electricity market directive, a new risk preparedness regulation and a greater role for the EU Agency for the Cooperation of Energy Regulators (ACER).⁵² The new electricity market design rules were adopted on 21 May 2024 and entered into force on 16 July 2024.⁵³

These changes will adapt current EU market rules by:⁵⁴

- allowing electricity to move freely throughout the EU energy market through cross-border trade, more competition and better regional cooperation
- enabling more flexibility to accommodate an increasing share of renewable energy in the electricity grid
- fostering more market-based investments in the sector, while decarbonising the EU energy system
- introducing a new emissions limit for power plants eligible to receive subsidies
- improving planning to anticipate and respond to electricity market crisis situations, including through cross-border cooperation



United States

Pillar 4 of the U.S. Grid Modernization Strategy 2024 aims to develop “next-generation methods and tools for markets, policies and regulations for a grid that is efficient and capable of ensuring a reliable energy supply while achieving the Administration’s deep decarbonization targets.” The scope of this pillar includes “policies and regulations at the federal, tribal, regional, state and municipal levels; market designs to enable just and equitable integration of all clean energy resources; and economic valuation that incorporates and prioritizes energy justice.” The strategy recognises the challenge of aligning of existing regulatory planning, utility planning and operational models with state and Federal goals.⁵⁵

Advanced transmission technologies, that enhance the capacity, efficiency and reliability of the existing power grid, have not been widely deployed in the U.S. The low cost of these technologies has been a barrier to their implementation, as utilities were not able to profit from deploying them. This is because under traditional “cost of service” business models, regulated utilities are allowed to recover their capital costs plus an allowed rate of return through electricity prices. This incentive structure means that utilities could make more money by pursuing capital-intensive projects such as new transmission lines, over cheaper advanced transmission technology projects. However, bills passed over the past couple of years in Montana, New Mexico, Utah and Indiana have authorised cost recovery for these technologies.⁵⁶

In June 2024, the Federal Energy Regulatory Commission shifted from incentivising to requiring utilities to deploy advanced transmission technologies, issuing an advanced notice of proposed rulemaking that included a framework for requiring dynamic line ratings on transmission lines.⁵⁷

Investment opportunities in the grid

Global investment in power grids and energy storage reached a record high in 2024. Grid spending rose 15% to US\$390 billion, with growth across all regions, notably in Europe. Investment in energy storage increased 36% to US\$54 billion, driven largely by developments in Asia and the United States. Despite this progress, the global grid infrastructure still needs a significant increase in investment to support the expansion of renewable generation.⁵⁸ To meet climate targets, grid investment needs to nearly double by 2030 to over US\$600 billion per year.⁵⁹

In this section, we look at what private equity can do within the current regulatory landscape. National grids are typically monopolised by transmission system operators (TSOs), but there are investment opportunities that support the grid, allowing further penetration of renewables and greater grid stability. Investment is needed to provide adequate system flexibility, without which there is a risk of rising amounts of surplus solar PV and wind power at times when output exceeds demand.⁶⁰

Leading economies, including the U.K., U.S. and across Europe, will see an unprecedented rise in expenditure over the next few years. Great Britain (England, Scotland and Wales) needs to increase its electricity transmission infrastructure five-fold.⁶¹ Investor-owned electric companies are predicted to invest around US\$158 billion on transmission construction between 2024 and 2027.⁶² £60 billion investment is required to meet the U.K. Clean Power 2030 target and 1,000 km of onshore and over 4,500 km of offshore transmission lines and cables need to be added to the network.⁶³

In Europe, € 472 billion of investment will be required for transmission grid developments until

2040, including to double the amount of cross-border transmission infrastructure.⁶⁴ US\$420 billion is needed for investment in offshore transmission assets.⁶⁵ In the U.S., investor-owned electric companies are set to invest around US\$158 billion on transmission construction between 2024 and 2027.⁶⁶

While electricity generation is a competitive wholesale market, transmission and distribution are historically regulated monopolies (for example the National Grid, Scottish Power and SSE in the U.K.). However, there are some opportunities for competition among independent distribution network operators and retail to end-user markets.⁶⁷

A number of economic and market opportunities exist relating to ancillary services. Ancillary markets include frequency measures, voltage measures, supply reconstruction and operational management. Investors can also benefit from long-term contracts with TSOs (Transmission System Operators) and DSOs (Distribution System Operators) relating to grid services, as well as the enhanced asset value from new revenue streams.⁶⁸

Different types of transmission are required to achieve decarbonisation and security of supply objectives and have varying opportunities for third-party investors. High-voltage (HV) transmission investments include direct current (DC) or alternating current (AC) variants.⁶⁹

These are ready for third party investment:⁷⁰

- Offshore HVAC or HVDC lines connecting windfarms (GB)
- HVDC interconnectors (connecting GB to Europe)

These have the potential for some third-party investment:⁷¹

- Offshore hybrid assets (U.K. and Europe)
- Standard AC transmission lines (U.K.)
- HVDC lines connecting two parts of the same system or “bootstraps” (U.K.)

Third-party investment is growing under the cap and floor model in U.K., introduced by Ofgem and the U.K. Government to unlock investment into long-duration energy storage (LDES). LDES technologies contribute to decarbonising and making our energy system more resilient by storing electricity and releasing it when needed.⁷² The regime, that sets a cap at the cost of debt and a floor at cost of equity, will ensure investors receive a minimum amount of revenue to enable investment in LDES assets.⁷³ Several projects are already operational under the cap and

floor pilot scheme, which benefits both consumers and developers.⁷⁴

Electricity interconnectors developed under the cap and floor regime will earn revenue from the allocation of capacity to users who want electricity to flow between the U.K. and its neighbours. Interconnectors may also earn additional revenue streams, including participating in the U.K. capacity market or providing services to system operators.⁷⁵ Meanwhile, the CATO (competitively appointed transmission owner) framework will allow competition in U.K. onshore networks,⁷⁶ and independent distribution network operators licensed by Ofgem will increase competition in the U.K. distribution market.⁷⁷

Longer-term procurement frameworks are increasing in popularity. For example, TenneT awarded US\$5.7 billion of framework agreements with several cable suppliers for 7000km of HVDC projects and RTE has entered into contracts worth US\$1 billion for cable supplies for projects through to 2028.⁷⁸

“Leading economies, including the U.K., U.S. and across Europe, will see an unprecedented rise in expenditure over the next few years.”



Successes and lessons learned from ambitious grid modernisation

Case studies

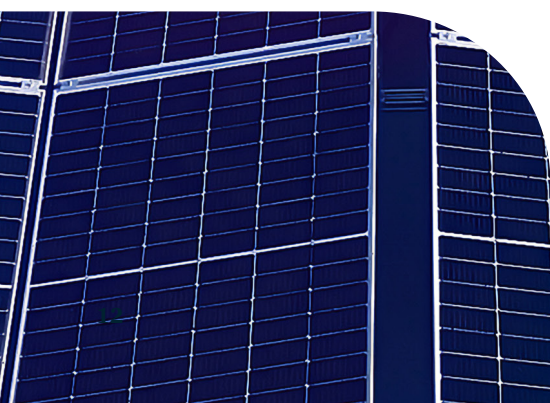
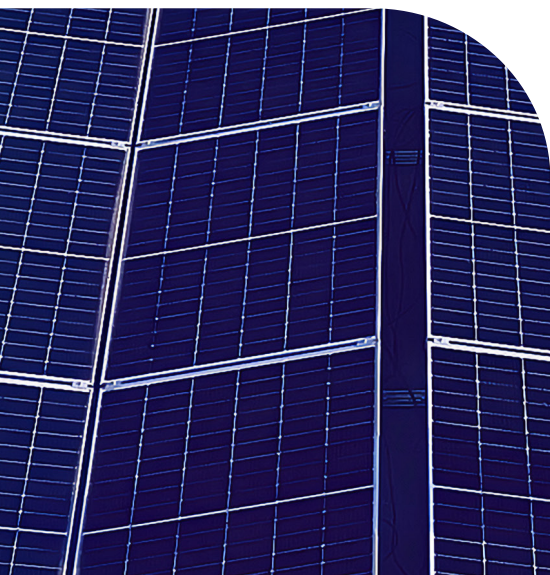


GREAT BRITAIN

National Grid ESO and flexible balancing services

The National Energy Systems Operator (NESO) procures services to balance demand and supply, and to ensure the security and quality of the electricity supply across Britain's transmission system.⁷⁹ Inertia, frequency, voltage and thermal all play key roles: inertia helps maintain stability; frequency ensures the flow of electricity is consistent; voltage regulates the power level; and thermal manages the heat generated. Together, these components ensure a consistent and reliable power system.⁸⁰

In July 2025, NESO opened a three-week evidence window for projects holding a U.K. grid connection agreement, to reform Britain's 738 GW connections queue. It is the first practical step in NESO's plan to cancel the first-come, first-served system that has allowed unviable and speculative ventures to block ready-to-build wind, solar and storage schemes. Shovel-ready projects aligned with the government's Clean Power 2030 ambition will receive confirmed modification offers, including updated energisation dates, site data and reinforcement requirements. Reforming the queue is central to the government's Plan for Change, which aims to unlock up to £40 billion a year of private investment and double onshore wind capacity, alongside rapid deployment of other renewables. NESO plans to publish the list of successful projects from September 2025 and begin issuing revised connection offers in autumn, starting with schemes due online in 2026 – 27. Projects connected at transmission level, and large embedded generators, must submit evidence directly to NESO, while smaller distribution schemes will file through their distribution network operator.⁸¹





GERMANY

Grid modernisation and challenges

Germany is accelerating the modernisation and expansion of its power grid, expanding and optimising transmission and distribution infrastructure to help with the integration of renewables. Electricity generation is mainly in the north of Germany, while most industry is in the west and south. While planning procedures for accelerating transmission network growth have improved, Germany has approximately 800 DSOs, making it challenging to implement advanced grid management technologies. While they are lagging behind in digitalisation, the country is seeing large-scale, market-driven energy storage development. Looking ahead, the German regulator stresses the importance of maintaining the pace of grid expansion and accelerating the digitalisation of distribution operators.⁸²



SOUTH AUSTRALIA

100% renewable energy

South Australia (SA) is aiming for 100% renewable energy by 2027. Wind and solar power grew to 75% across the region in 2023. The state government's focus is on stability, flexibility and reliability, with more large-scale battery storage and hydrogen included in the plan for excess power from wind and solar. The secure and reliable system is made possible thanks to investment in storage, smarter management and grid flexibility. The key to SA's success is not just technical, but also political, as there is bipartisan support for renewable energy.⁸³

The electricity system has seen rapid change in the state, with a lot of investment and fast uptake of rooftop solar, battery storage, solar farms and wind farms. New technologies are allowing the bidirectional flow of electricity, with electricity generated by users and sent back into the grid. However, operating a two-way system originally built for one-way, is creating new balancing issues.⁸⁴



INDIA

Green Energy Corridor

Since 2015, India has been working on transmission infrastructure to connect solar and wind capacity with urban demand centres. The Green Energy Corridor (GEC) comprises both inter- and intra-state transmission systems, along with the setting up of renewable energy management centres and control infrastructure such as reactive compensation and storage systems.⁸⁵ The project has faced challenges, with delays caused by right-of-way issues, substation land acquisition, low bid turnout in various projects resulting in re-tendering, court cases, forest clearances and clearance issues relating to the critically endangered Great Indian Bustard. Despite these obstacles, Green Energy Corridor Phase-I is nearing completion, with 20 GW of 24 GW transmission capacity commissioned. The project spans eight states to evacuate renewable power efficiently. Phase-II is progressing fast, while Phase-III is expected to roll out in FY26.⁸⁶





Outlook

A vast amount of transmission infrastructure needs to be built and third party investment is critical. However, the potential role for third parties currently varies significantly across jurisdictions. Concurrent demands from countries with strong decarbonisation agendas have made parts of transmission a suppliers' market, while increasing costs are making all types of transmission development more challenging.⁸⁷

Distributed energy resources are creating new opportunities and challenges. Small-scale, clean installations located behind consumer meters, such as PV, energy storage and EVs, are increasingly widespread and are already transforming energy systems. New and varied technologies allow consumers to be more proactive and are encouraging new players to enter power markets, such as aggregators who pool together small-scale resources and act on their owners' behalf. With bidirectional electricity flow, consumers are increasingly able to take control of their own energy demand through a complex web of interactive smart energy devices.⁸⁸

Policy interest in system upgrades has grown, as has flexibility through battery storage, demand-side response, sector coupling, the use of distributed resources and the integration of new actors such as aggregators and local energy communities. Several countries have mandated that new variable renewable energy capacity be paired with storage capacity. Market instruments such as variable network tariffs and constraint markets have emerged as tools to balance power networks.⁸⁹



Conclusion

The electricity grid must evolve quickly to underpin the transformation of global energy systems. It is tasked with integrating renewable energy resources at an unprecedented scale, while maintaining flexibility, resilience and affordability. As this paper has explored, the transition from centralised, fossil-fuel-based power systems to more decentralised, bidirectional smart grids presents both immense challenges and unique opportunities. From the technical complexities of balancing supply and demand, to the regulatory shifts needed to incentivise private investment, we need coordinated action across sectors and borders.

Recent events, such as the Iberian Peninsula blackout, underscore the urgency of upgrading grid infrastructure, improving ancillary services and deploying advanced technologies, including grid-forming inverters and battery energy storage systems. At the same time, examples from the U.K., Germany, South Australia and India show that meaningful progress is possible when supportive policy frameworks and innovative technology align.

As electricity demand continues to rise and the share of variable renewable energy grows, so too does the need for capital to flow into smarter, more flexible infrastructure. Governments and private investors alike have crucial roles to play in this transformation. Whether through direct investment in high-voltage transmission lines, participation in ancillary service markets, or support for distributed energy solutions, investment can help shape a grid that is more adaptive, resilient and sustainable.

Modernising the grid should not be seen not as a constraint on decarbonisation, but as its enabler. The technology needed to integrate energy from renewable sources will serve to strengthen the grid and with strategic investment, regulatory reform and continued innovation, our future power systems can be more secure and efficient.

OPINION PIECE. PLEASE SEE IMPORTANT DISCLOSURES IN THE ENDNOTES.

Endnotes

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