

Briefing 45 Adapting Electricity Grids: Technological and Scientific Challenges

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Summary

- *To cope with the growth in renewable energies and new uses, the effects of climate change and cyber threats, the French electricity grid needs to undergo a major transformation.*
- *This adaptation will require large-scale investment and long-term governance, coordinated at European, national, regional and local levels, between now and 2040.*
- *The success of this transition depends on stepping up research, innovation and skills development.*

Jean-Luc Fugit, Member of the National Assembly

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■ **Background: networks that must accommodate new electricity sources and respond to new uses and risks**

Since they emerged in the late 19th century, electricity grids, which have gradually become interconnected, have been designed around centralised generation facilities and a hierarchical distribution of electricity to consumers.

The French electricity grid was built on this same principle in the second half of the 20th century, structured primarily around large nuclear, hydroelectric and fossil fuel power stations, and is now interconnected with other European grids.

This model now needs to adapt to the rapid growth of decentralised renewable energy, particularly wind and solar power. These sources have some distinctive characteristics: they are generally scattered across the country, sometimes in areas far from consumption centres, and the power they deliver is variable and difficult to control. This results in a reconfiguration of electricity flows that has significant implications for grid stability, particularly in terms of the need to balance supply and demand in real time.

In addition to this transformation in electricity generation methods, new uses are becoming increasingly prevalent, such as electric vehicles (over 5% of French cars in April 2025), coupled with the rollout of charging points (160,000 as at 31 March 2025),¹ heating and cooling in the residential and commercial sectors, particularly with the installation of heat pumps (50 TWh of renewable heat produced in 2023),² the proliferation of data centres, new industries (batteries, hydrogen electrolysis, synthetic fuels,

etc.), and the electrification of industrial applications (industrial heating, pumps and compressors, etc.). These new uses are changing when and where electricity is consumed, placing additional strain on the electricity grid.

The risks associated with climate change add further complexity to this dynamic. The increasing frequency of extreme events such as storms, heatwaves and flooding threatens the resilience of physical infrastructure including overhead lines, transformers and substations. At the same time, the growing digitalisation of the grid, with the rollout of sensors, monitoring systems and smart meters, exposes infrastructure to heightened risk of cyberattacks.

■ **Three major challenges for smooth grid operation**

Integrating electricity from renewable energy sources, mainly wind and solar power, into a grid designed for centralised generation from a small number of controllable power stations, presents a threefold technological challenge.

➤ **Strengthening infrastructure**

In a centralised system, electricity flows follow a mainly unidirectional logic, with large generation centres injecting energy into the high-voltage transmission network, which then transports it to distribution networks and ultimately to end consumers. The infrastructure has been designed and sized for this top-down configuration, with predictable flows.

The growing integration of decentralised sources means that electricity flows are now bidirectional, since distribution networks, which were initially passive recipients, are now also collectors of locally generated

energy. They must therefore be adapted to manage reverse flows and prevent local congestion. As the overall distribution of flows has changed, the transmission network must also be resized and adjusted accordingly.

Furthermore, the proliferation of connection points – from small residential installations to larger-scale operations – makes grid oversight and security more complex. This increasing density requires not only enhanced monitoring and control capabilities, but also stronger cybersecurity measures to limit vulnerability to growing threats in an increasingly interconnected and computerised grid.

➤ Ensuring greater flexibility

The variability of wind and solar generation across monthly, weekly and daily timescales requires modifications to ensure the system can maintain a constant balance between generation and consumption, which is a prerequisite for security of supply.

Flexibility has emerged as the main tool for maintaining this balance, despite the growing share of non-controllable sources in France and Europe. Flexibility can be defined as *“the ability of a generation, consumption or storage facility to modulate upwards or downwards its injection into or withdrawal from the grid”*.³ It can be broken down into supply-side and demand-side flexibility.

Supply-side flexibility can take several forms: controllable peak-load power plants, designed to respond to demand peaks (i.e. periods of exceptionally high electricity consumption) or situations where other generation facilities are insufficient; strengthening interconnections with neighbouring countries, enabling the export of surpluses or the import of shortfall electricity; various forms of storage (batteries, pumped hydro, hydrogen, etc.);⁴ and *“oversizing renewable infrastructure, combined with curtailment strategies limiting excess generation”*.⁵

Demand-side flexibility can also take several forms. For example, pricing based on peak, off-peak and even “super off-peak”⁶ periods can steer consumption towards times of low demand, such as at night, or high solar generation, such as in the afternoon. Smart devices can automate the shifting of consumption across various sectors, including the building sector, through intelligent building management systems; the transport sector, by controlling electric vehicle charging without necessarily waiting for the widespread adoption of vehicle-to-grid technology;⁷ and industry.

➤ Maintaining grid stability

Another key challenge in integrating renewable electricity is grid stability, which is measured in terms of frequency (set at 50 Hz in Europe), voltage and resistance to short circuits.⁸

Until recently, this stability relied on the synchronous alternators used in nuclear, hydroelectric and fossil fuel power plants. These rotating machines not only deliver

controllable generation, but also provide essential system services, including mechanical inertia to dampen frequency variations, voltage support through injection or absorption of reactive power, high short-circuit power to ensure the effectiveness of grid protection systems, and grid-forming capability,⁹ which involves generating a voltage waveform synchronised to the system frequency, thereby establishing the specific reference frequency and phase necessary for the coordinated operation of other connected equipment.

With the rise in the number of wind and solar sources connected to the electricity grid via inverters,¹⁰ the number of rotating machines is declining. However, these new sources do not stabilise the grid in the same way as conventional power plants. They even depend on the signal from plants with rotating machines to function correctly.

To compensate for the drop in inertia, solutions such as fast frequency response¹¹ or synthetic inertia¹² enable inverters to adjust the power they inject, but these approaches are insufficient if the instantaneous share of wind and solar exceeds a certain threshold, estimated by specialists at between 60% and 80%.^{13 14}

Synchronous condensers – electromechanical devices capable of dampening frequency deviations and providing rotating machine services without net active power generation – offer a complementary solution.^{15 16} Already used in industrial settings and recently deployed in South Australia,¹⁷ their large-scale rollout has yet to be fully assessed.¹⁸ Other solutions are under development, but still require further research and development for deployment at scale.

■ Large-scale investment programmes to strengthen electricity grids

In 2024, the combined share of wind and solar photovoltaic energy in national electricity generation remained below 15%, meaning that the challenges associated with integrating them into the electricity grid were not as acute in France as, for example, in Germany or Spain, where this share stood at 45.3%¹⁹ and 40.2%²⁰ respectively. However, the rapid growth of these sectors is expected to lead to a significant increase in their contribution by 2050. The investments needed to adapt and modernise electricity infrastructure must therefore be planned to keep pace with this transition and maintain the stability of the energy system.

The French electricity grid essentially consists of two main levels: a “bulk transmission” network at extra-high voltage (400 kV and 225 kV) transporting electricity over long distances,²¹ to which a high voltage (90 kV and 63 kV) sub-transmission network is connected; and a medium (20 kV) and low voltage (400 V and 230 V) distribution network.

Despite these differences, the challenges facing transmission and distribution network operators –

modernising infrastructure, new energy sources, new uses and new risks – are comparable.

France's Réseau de Transport d'Électricité (RTE), with its workforce of 10,500, operates a network comprising approximately 106,000 kilometres of extra-high and high voltage lines. RTE has embarked on a €94 billion investment programme running to 2040, structured around a Strategic Plan for the Development of the Electricity Transmission Network to 2040 (SDDR).²² This plan focuses on three priorities: upgrading the network and adapting it to climate change, at an estimated cost of €24 billion; connecting new consumers (industry, data centres, hydrogen production, etc., with an estimated total capacity of 21 GW) and new generation facilities (offshore wind, new nuclear, onshore renewables, batteries), requiring €53 billion, of which €38 billion is allocated to connecting offshore wind; and strengthening the grid's structure to enable it to support the transformation of the electricity system and the associated changes in flows, at a cost of €17 billion.

Enedis, which operates France's main public electricity distribution network, manages 1.4 million kilometres of medium and low voltage lines with a 40,000-strong workforce. Alongside the local distribution companies (LDCs), which serve around 5% of customers, Enedis has a €96 billion investment plan for the period up to 2040.²³ This plan covers, in particular, the connection needs of renewable energy generation facilities (95% of which are connected to the distribution network), driven by low-voltage solar photovoltaic installations, electric vehicle charging infrastructure and buildings. In 2024, Enedis connected 5.5 GW of wind and solar capacity and 5.1 GW of charging points. Projections to 2035 anticipate a dramatic increase in connected generation capacity (from 46 to 100 GW) and in the volumes of energy distributed (from 77 to 160 TWh), requiring infrastructure upgrades, particularly to primary substations, to manage the delivery of injected power. The plan also includes a component, equivalent to a quarter of the total investment, specifically for modernising the distribution network and strengthening its resilience to increasing climate hazards such as storms, fires, flooding and heatwaves.

At the same time, local authorities²⁴ are playing an increasingly central role in energy planning, given their detailed knowledge of the local area, social constraints and development opportunities.

■ The need to step up research

As highlighted at the public hearing organised by the Office on 20 March 2025 on "The future of electricity grids: scientific and technological perspectives", a vast field of research is opening up to ensure that electricity grids can adapt to current and future challenges. The areas that need to be addressed span a wide range of scientific and technological topics.

Historically, French research on electricity grids has mainly been driven by industry, particularly within EDF and subsequently Enedis and RTE, with less emphasis on academic research than in other European countries.

One major area of research is electrical engineering, sometimes called "power engineering", a discipline long overlooked outside industrial circles because it was mistakenly perceived as outdated. Today, however, it is proving more essential than ever in a world where electricity grids are undergoing profound change. Several cutting-edge developments were presented at the public hearing, including improving detailed understanding of electricity grid balancing to prevent instabilities and systemic failures, refining DC to AC converters to ensure the efficient connection of wind and solar power, deploying interoperable multi-terminal high-voltage grids²⁵ to optimise the integration of offshore wind, optimising medium-voltage architectures, chiefly to support the growth of solar photovoltaics and reduce conversion losses, and developing dynamic cables for floating offshore wind power and solutions using superconductivity, in order to improve overall energy efficiency. These innovations require substantial investment, which will depend on effective coordination between public and industrial research to bridge the gap between scientific advances and practical, competitive applications.

Mathematics and algorithms also play a fundamental role, as the large-scale integration of renewable energy introduces uncertainty and intermittency. In particular, it is necessary to model the grid's physical flows that are subject to complex constraints, optimise the use of infrastructure and storage, and leverage flexibility to maintain the supply-demand balance at every timescale, from real time to the time frame of the long-term investment programmes. This research into how to optimise systems despite inherent uncertainty incorporates physical constraints, climate variability, market price volatility and socioeconomic scenarios.

Artificial intelligence (AI) has an enabling role in forecasting generation and consumption, optimising investment, identifying maintenance requirements (by analysing drone images, for example) and automating operations. AI is also used in scenario generators that take into account several correlated variables, such as temperature, wind and cloud cover, to provide better predictions of future situations.

With the digitalisation of infrastructure, networks are exposed to new threats, leading to an increased collaboration with stakeholders in the digital sector to strengthen cybersecurity and address challenges such as post-quantum cryptography.²⁶

Lastly, research must also incorporate environmental and climate resilience. Infrastructure must be designed to withstand extreme events such as storms, heatwaves and fires, factor in life-cycle analyses to reduce its impact on

biodiversity, and adapt to the geopolitical and industrial developments that affect supply chains and European technological sovereignty.

France has an advantage in several of these areas. To safeguard this advantage and strengthen our national industrial capabilities over the long term as international competition, particularly from China, intensifies, we will need to mobilise additional resources, especially for academic research.

■ Building skills, attracting talent

The successful adaptation of the electricity grid depends not only on mobilising financial and technical resources, but also on the ability to recruit the specialists needed to deliver it.

In France, electricity grids employ nearly 100,000 people, almost half of whom work in jobs classified as “key” to the sector. With the large-scale investments planned, demand for these skills is expected to rise by 61% by 2030. Supporting this growth requires a substantial increase in recruitment, which is expected to reach around 9,000 appointments per year by 2030, totalling 43,000 new hires over five years for these “key” jobs alone.²⁷

Enedis, RTE and professional bodies launched a partnership in 2023 called “Les Écoles des réseaux pour la transition énergétique” (Grid Schools for the Energy Transition). The “Training Assessment”, published on 27 November 2024 as part of this partnership under the France 2030 programme, highlights several areas for improvement, particularly for initial training: increasing capacity, especially on foundation courses such as the BTS Électrotechnique (electrical engineering technician qualification), developing more specialist training in electricity grids, and diversifying the talent pool through partnerships with universities to address shortages in engineering training. Further efforts are needed to raise the profile of electricity sector careers, particularly in higher education, where certain fields, such as electrical engineering, do not attract enough students given their importance to the sector.

■ The governance issue

The current transformation of the electricity system cannot be reduced to a technological evolution. It also depends on strategic choices regarding investment, long-term planning, scenarios leading to higher or lower electricity consumption and coordination between stakeholders. The grid’s infrastructure is inherently slow to change, with developments taking place over several years or even decades. The governance aspects of this transition therefore depend on the ability to coordinate effectively at national, regional and local levels, while ensuring consistency between climate ambitions and operational realities.

■ Recommendations

- Step up efforts to electrify end uses, by providing sufficient clarity to enable stakeholders to anticipate and plan accordingly.
- Speed up the rollout of smart energy flexibility systems in the building sector, in particular by leveraging the potential of refrigeration in the agri-food and retail sectors.
- Support the deployment of grid-connected storage facilities by creating a favourable regulatory framework.
- Adapt tendering procedures to encourage a more balanced geographical distribution of renewable generation facilities and limit grid costs.
- Improve the attractiveness and visibility of training pathways for electricity sector careers, in both secondary and higher education.

The Office’s websites:

<http://www.assemblee-nationale.fr/commissions/opepst-index.asp>

<http://www.senat.fr/opepst>

People consulted (listed alphabetically by organisation and name)

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- ¹ Electric and plug-in hybrid vehicle registration barometer. Key figures for April 2025, Avere-France.
- ² Key figures for renewable energies, 2024 edition, Data and Statistical Studies Department, p. 11. Renewable heat is energy extracted from the environment (air, water or soil), as opposed to the electricity or gas consumed by the heat pump.
- ³ The Strategic Dimension of Electricity System Flexibility: Opportunities in Europe, 30 April 2025, Cédric Philibert and Arthur de Lassus, IFRI, p. 11.
- ⁴ OPECST Science and Technology Briefing No. 11 – Electricity Storage, February 2019, Angèle Prévile, Senator.
- ⁵ Cédric Philibert and Arthur de Lassus, op. cit., p. 4.
- ⁶ Decision of the French Energy Regulatory Commission of 15 January 2025 proposing regulated electricity sales tariffs for consumers subscribing to a power rating of less than or equal to 36 kVA in mainland France and all consumers in non-interconnected areas.
- ⁷ Technology that enables electric vehicles to provide flexibility services to the grid by feeding electricity back into it and adjusting the charging speed.
- ⁸ The ability of the grid to absorb or withstand a short-circuit current without malfunctioning. A short circuit is a fault resulting from an accidental connection between phases or between a phase and earth, which causes a very high current, often 10 to 50 times greater than the normal current.
- ⁹ “Grid forming” refers to the ability of certain electricity sources to actively contribute to grid stability by controlling their own frequency and voltage, even when they have no external reference.
- ¹⁰ With some exceptions, wind turbines and photovoltaic panels produce direct current (DC), which must be converted by an inverter into the alternating current (AC) required by the grid.
- ¹¹ The ability of an inverter to react quickly (usually within 0.5 to 2 seconds) to a change in the frequency of the electricity grid by adjusting the power injected up or down to help stabilise the system.
- ¹² The ability of an inverter to mimic the inertial behaviour of power plants with rotating machines by very quickly (within tens to hundreds of milliseconds) adjusting the power injected if grid frequency changes.
- ¹³ Conditions and Requirements for the Technical Feasibility of an Electricity System with a High Share of Renewables by 2050, January 2021, OECD/IEA and RTE, p. 9.
- ¹⁴ Minutes of the OPECST public hearing of 20 March 2025 on “The future of electricity grids: scientific and technological perspectives”.
- ¹⁵ High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters, 2021, ENTSO-E, p. 7.
- ¹⁶ Rotating machines from decommissioned conventional power plants can be converted into synchronous condensers at low cost. See Synchronous Condensers as a Viable Inertia Support Mechanism on the Future South African Grid, Energy for Sustainable Development, Volume 69, 2022, Angélique Roux, Bernard Bekker, Amaris Dalton.
- ¹⁷ Inquiry Into South Australia’s Renewable Energy Competitiveness, 10 August 2022, South Australian Productivity Commission, p. 71 and Repurposing Existing Generators as Synchronous Condensers, Report on Technical Requirements, 22 June 2023, DigSILENT for ARENA.
- ¹⁸ OCDE/IEA and RTE, op. cit., p. 9.
- ¹⁹ Electricity: Germany’s Renewable Energy Production Reaches Record-Breaking Levels, 14 March 2025, German Embassy in Paris.
- ²⁰ Spanish Electricity System Reports 2024, 18 March 2025, Red Eléctrica de España (REE).
- ²¹ Electrical transmission losses are mainly resistive losses, described by Ohm’s law and quantified by the expression: $P_{\text{losses}} = R \times I^2$, where R is the electrical resistance of the conductor (in ohms) and I is the current intensity (in amperes). Since the power transported is the product of the current and the voltage (in volts), $P_{\text{power}} = I \times U$, transporting electricity at very extra-high voltage minimises the current and therefore optimises the energy efficiency of the transport.
- ²² Ten-Year Network Development Plan, 21 March 2025, RTE.
- ²³ Network Development Plan, January 2023, Enedis.
- ²⁴ As concession-granting authorities, local authorities own the electricity distribution networks in their areas and delegate their operation to distribution network operators such as Enedis or local distribution companies (LDCs) through concession contracts.
- ²⁵ A network connecting several offshore wind turbines locally, enabling their combined output to be transmitted to the mainland via a shared cable, thereby avoiding the need for individual connection cables for each turbine.
- ²⁶ A branch of cryptography aimed at keeping information secure from attackers with hypothetical quantum computers.
- ²⁷ Employment and Skills Needs in the Electricity Grid Sector, Training Assessment, 27 November 2024, French government and Government and the “Écoles des réseaux pour la transition énergétique” partnership.