Le réseau de transport d'électricité

R&D **Strategic Roadmap**

2025-2028

Summary

Introduction

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RTE's Research and Development (R&D) department innovates to enable RTE to carry out its current and future missions in an efficient and resilient manner. It aims to identify and successfully implement the transformation of the power transmission system, in line with French and European energy policies (energy and ecological transition, sovereignty, economic competitiveness). This helps to anticipate risks and opportunities in order to better prepare for the future.

R&D is primarily funded through an incentive-based regulatory mechanism under the TURPE framework. This report describes the R&D roadmap for the "TURPE 7" period, running from 2025 to 2028.

The anticipated transformation of the energy system, outlined in RTE's recent prospective studies, justifies increased R&D needs for the "TURPE 7" period. This roadmap identifies three priority areas, broken down into 11 specific objectives, further divided into 37 topics. These are outlined in Chapter 2.

To carry out these R&D topics and achieve the corresponding objectives, RTE is adapting its R&D model based on past experience, changing context and new challenges. These adjustments mainly concern increased collaborative research and changes to the allocation of R&D efforts over different maturity levels. They are presented in Chapter 3.

Objectives of the 2025-2028 R&D plan

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2.1 Preparing for a major and phased transformation
of the French energy system by embracing three fundamental dimensions

The *Energy Pathways to 2050* study, published by RTE in 2021, outlines scenarios for the profound transformation of the French energy system to reach carbon neutrality by 2050.

These scenarios share several common features: a reduction in final energy demand (driven by energy efficiency and conservation) combined with a rise in electricity demand (notably through the electrification of end uses), resulting in an increased share of electricity. At the same time, renewable energy sources take up a growing share of power generation.

The 2023-2035 Multiannual adequacy report study, published in autumn 2023, updates the first phase of the *Energy Pathways to 2050*, marking the halfway point toward the country's carbon neutrality target. This update accounts for a new context through an additional "successful acceleration" scenario, in line with the draft of the French government's national strategy for energy and climate, submitted for public consultation. This scenario explores the implications of a context of increased geopolitical and economic tension (war in Ukraine, energy crisis), France's intention to strengthen its industrial and energy sovereignty and new climate and decarbonisation ambitions.

FIGURE Electricity demand trajectory in the 2023 Multiannual adequacy report and the *Energy Pathways to 2050* (left), sector breakdown in the reference trajectory by 2035 (right).

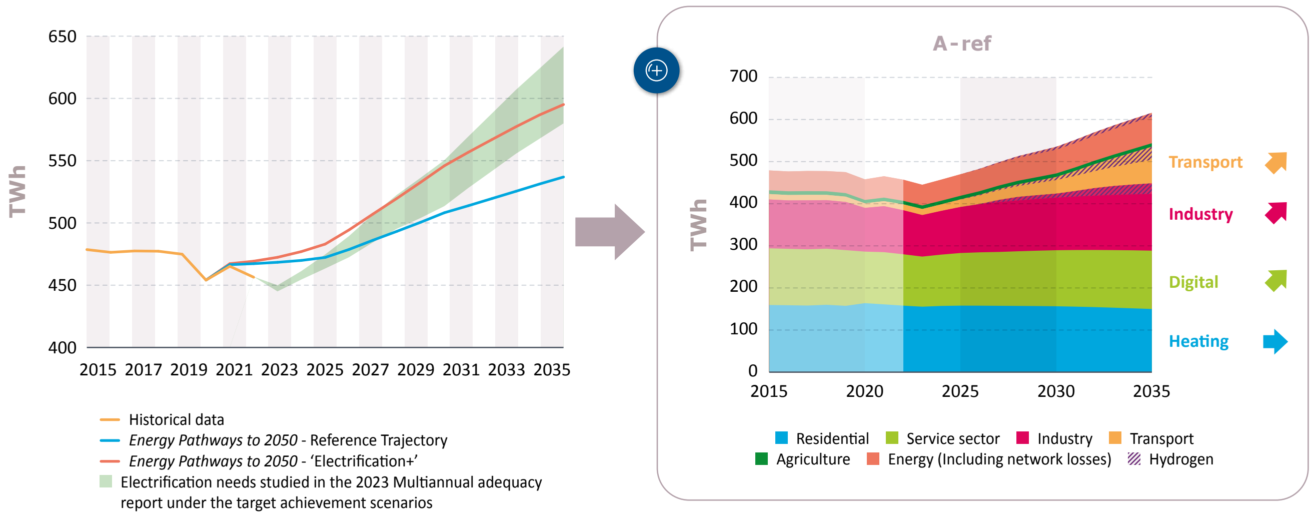
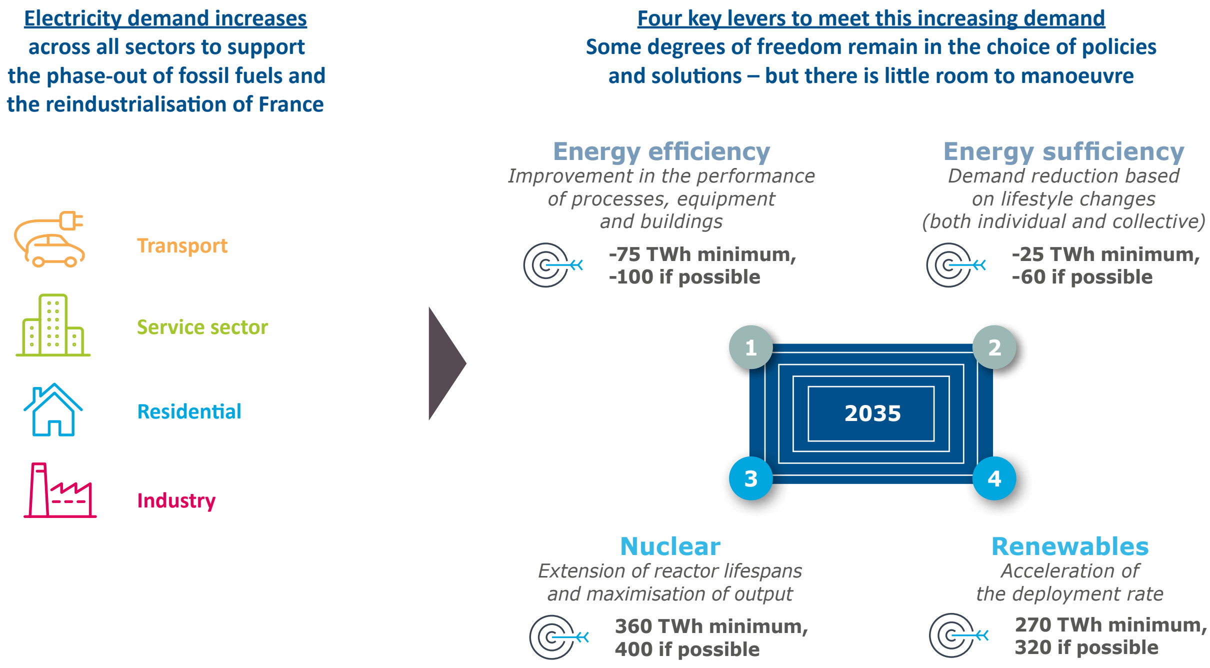


FIGURE Levers identified to achieve the climate and energy sovereignty objectives by 2035



To explore the network implications of these generation scenarios, RTE published a new *network development plan* (SDDR) in 2025. This strategic programme-plan identifies the infrastructure development needs of the electricity transmission network for the 2025-2040 period and proposes structural and technological options to address those needs, with an optimised and sequenced approach. It reveals a need for accelerated investment, totalling approximately €100 billion over the 2025-2040 period.

Contributing to the successful implementation of France's 2025 network development plan is the first strategic priority that must guide the R&D roadmap for TURPE 7. A successful network adaptation should be economically efficient, resilient to uncertainty and ensure access and power quality delivered within acceptable timeframes.

Beyond the challenge of upgrading network infrastructure, the transformation of the French energy system also requires a fundamental overhaul of power system operation, to adjust for the following disruptions:

- The operating principles of the power system are becoming increasingly complex, with growing uncertainty in power injections, greater variability in power flows – both locally and across Europe – and more complex interactions with distribution networks.

- The massive introduction of power electronic interface converters (for connecting generation sites, consumption sites and HVDC lines to the grid), whose behaviours are less "linear" than traditional network components and which do not inherently provide any stabilising and self-regulating effects (such as synchronous generation mechanical inertia and load voltage- and frequency-sensitivity), is gradually altering the behaviour of the grid. This evolution threatens, in the long term, dynamic stability, protection and defence schemes, as well as compliance with electricity quality criteria, particularly voltage quality.

- At the same time, the network control architecture is evolving to incorporate more distributed automation within the system. This serves a dual purpose: to enhance the grid's capacity to accommodate new uses and to leverage advanced automation to manage part of the operational uncertainty, particularly over very short timeframes.

- Demand-side flexibility must be developed as a priority and at scale to become a fully integrated component of the electricity mix. It is expected to make a vital contribution to supply continuity and system optimisation by better aligning consumption with the production of decarbonised electricity, as highlighted in the analyses of the 2023-2035 Multiannual adequacy report.

- The operation of the power system will have to contend with major construction stages, as well as the associated equipment outages for maintenance, which will weaken the power grid.

Research and development of solutions for transforming power system operation thus constitute a second priority for TURPE 7.

Finally, RTE's industrial strategy must also consider external factors that may affect, to varying degrees of certainty and impact, the development plans and the reliable operation of the electricity transmission system, the energy sector, and ultimately society as a whole. The main external disruptive factors identified to date are:

- Climate change, which will likely impact a wide range of RTE's missions, with projections becoming more pessimistic each year, thereby reinforcing the necessity and urgency of preparing the French power system to address it[1].

- The risk of increased global competition for access to the materials and technologies needed to develop future energy systems. Recent signals suggest that globally integrated supply chains could experience recurrent failures due to the combined effects of massive demand growth[2] (aging infrastructure, new developments), critical raw material shortages and geopolitical tensions.

- New regulatory requirements on eco-design that compel actors to consider environmental and biodiversity protection as well as efficiency in the use of resources. These requirements may penalise less sustainable industrial practices.

Furthermore, the recent deterioration of the geopolitical and economic climate has led to a period of increased instability. This context strengthens the need for RTE to have robust foresight capabilities and analytical tools to assess the resilience of industrial strategies to potential external disruptions.

Research and development of solutions to anticipate and address major external risk and disruption factors thus constitutes the third priority for TURPE 7.

1. RTE was involved in the work related to the Reference Warming Trajectory for Climate Change Adaptation (TRACC), which establishes a reference scenario of approximatively +4°C average warming across metropolitan France and will have to comply with the upcoming National Climate Change Adaptation Plan.
2. As documented in the International Energy Agency's (IEA) report "Electricity Grids and Secure Energy Transitions", published in November 2023.

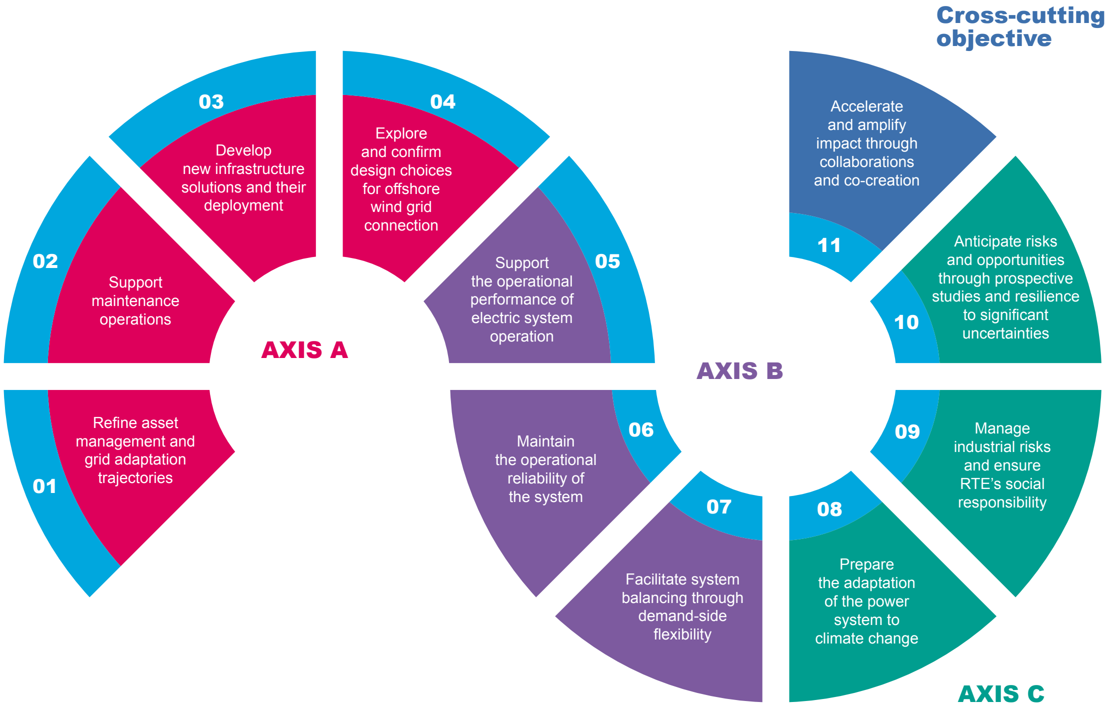
In summary, the R&D roadmap for the TURPE 7 period has been developed around three priority areas (or fundamental strategic dimensions for the future transmission network):

A. Contribute to the successful achievement of France's network development plan (SDDR) trajectories

B. Contribute to the transformation of the operation and management of the power system

C. Anticipate and consider major external risk and disruption factors

The three strategic dimensions mentioned above are broken down into 11 R&D objectives that specify the challenges RTE's R&D activities aim to address. To achieve these 11 objectives, 37 areas of activity or "R&D topics" have been identified, which will focus the work of the Programmes and Roadmaps during the TURPE 7 period.



2.2 Contributing to the successful implementation of the SDDR investment trajectories

Four R&D objectives will guide the R&D roadmap during the TURPE 7 period to contribute to the successful achievement of the SDDR 2025 trajectories (*i.e.*, an economically efficient adaptation of the grid, resilient to uncertainties, with controlled technical and technological risks, ensuring the expected quality of network access and power supply service and implemented within appropriate timeframes):

A1. Refine asset management and grid adaptation trajectories through techno-economic modelling, risk analysis and robust optimisation.

A2. Support the operational performance of maintenance through enhanced network inspection and asset condition diagnostics.

A3. Invent new infrastructure solutions and deployment methods to facilitate and accelerate the grid adaptation to future uses.

A4. Explore and validate design options for connecting deep offshore wind power.

These objectives have already guided the R&D roadmap during the TURPE 6 period, in line with the trajectories outlined in France's 2019 network development plan (SDDR). However, RTE perceives a strong need for acceleration in TURPE 7, reflecting the significant ramp-up in investment trajectories[3]. Indeed, R&D results must be achieved early enough to deliver industrial benefits by 2040.

A1. Refine asset management and grid adaptation trajectories through techno-economic modelling, risk analysis and robust optimisation

France's 2025 network development plan (SDDR) identifies the needs for the evolution of the electricity transmission network infrastructure over the 2025-2040 period and proposes structural and technological options to meet these needs, with an optimised and sequenced overall vision. The corresponding investment needs are experiencing strong growth and acceleration, totalling around €100 billion over the 2025-2040 period. The vision for France's network development plan (SDDR) will be further developed and detailed in subsequent investment programmes.

The forecast trajectories of France's network development plan (SDDR) present major industrial challenges in multiple areas: pace of execution, availability of skilled labour, capacity of supply chains and subcontractors, service continuity during construction, financing capacity and tariff evolution. To better manage the risks posed by these challenges, it will be essential to develop methods that enable coherent optimisation of grid renewal and expansion decisions, facilitate trade-offs and prioritisations based on a risk quantification framework representative of the operational consequences, assess the precedence of available options according to multiple criteria and evaluate the robustness of choices against uncertainties in underlying assumptions. These methods must also incorporate consideration of new flexibilities, such as demand-side modulation services and automated systems deployed in the network, to harness these levers as alternatives to infrastructure

3. A tripling of investment trajectories between the vision developed in 2019 and that of the 2024 SDDR, rising from 33 billion euros over the 2021-2035 period

Location of major current and future major centres of generation and demand

Projected changes in transmission level power flows by 2040

Congestion in 2040 in the event of a complete lack of reinforcement of the grid infrastructure

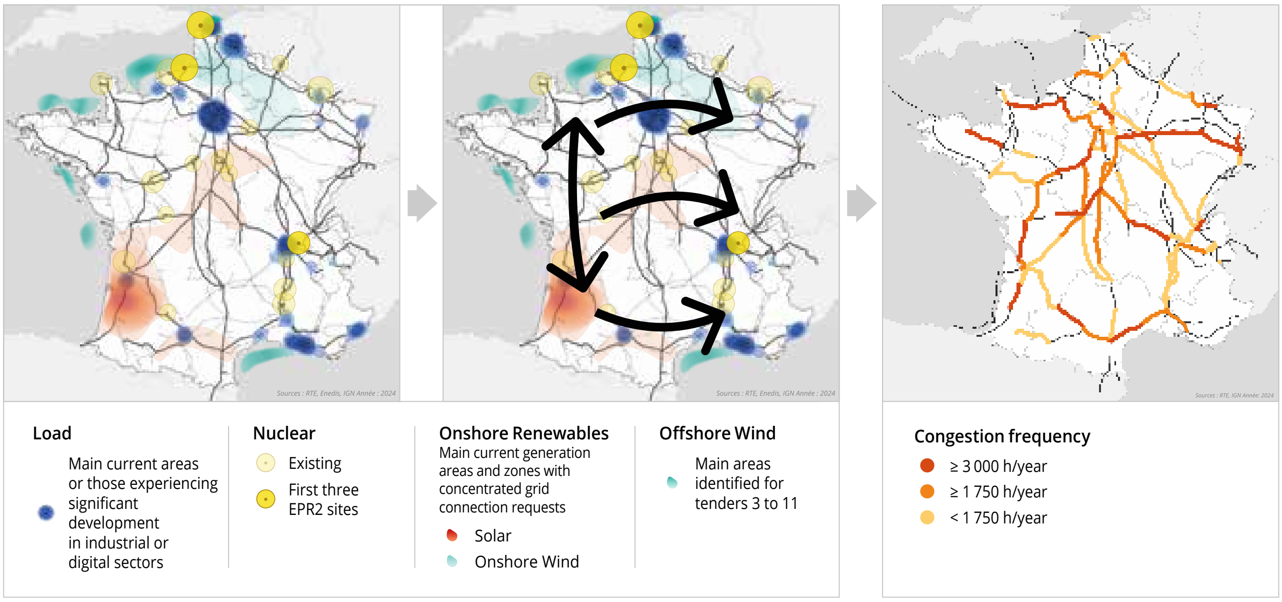


FIGURE Map of generation resources from the PPE 3 project, network flows and related congestion

development, while anticipating the operational impacts their large-scale deployment could entail. The stakes are high: identifying suitable optimisation levers could lead to potential savings in the hundreds of millions, or even billions, of euros across subsequent investment programmes[4]. Conversely, accurately representing the risks inherent in each option will be crucial for controlling costs associated with delays or mismatches between infrastructure and system needs – risks that could amount to several hundred million euros over the next fifteen years.

Moreover, in a context of major transformation in energy uses – characterised both by expectations of accelerated grid access and by significant uncertainties regarding the development dynamics of production and consumption sectors – reactive approaches to infrastructure adaptation based on demand are becoming increasingly difficult to implement. This raises the risk of a mismatch between the evolution of the grid and the evolution of energy uses. It therefore appears timely to equip RTE with methods and tools to plan grid development and connection capacity in a more proactive manner, anticipating future uses. This would require the ability to model the dynamic interaction between development plans and grid access requests (i.e., the capacity of users to adjust their location decisions in response to available capacity), and to have methods for the techno-economic evaluation of investment options that account for uncertainties in future energy uses.

4. With the objectives of achieving an optimisation gain of 0.5% to 1% on an investment trajectory of approximatively 100 billion euros.

The 2025-2028 R&D Plan aims to address this "A1" objective through work in two areas:

Network and connection study methods and tools

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Design new methods to support the construction of data sets for network adaptation studies, enabling coherent integration of different geographical scales – from modelling large-scale supply-demand balances at the pan-European level to projecting, at the regional level, development scenarios for various sectors and the resulting grid access requirements. ▸ Adapt network study methods and algorithms to better account for new flexibilities, whether related to demand response services or automated systems deployed within the grid, in order to harness these levers as alternatives to infrastructure development while anticipating the operational consequences that their large-scale deployment could cause (for example, the future capacity to carry out the necessary shutdowns for infrastructure maintenance).	Proofs of concept and demonstrations of minimum viable methods for building data sets and integrating flexibilities/automation systems (achievement of TRLs 5, 6, 7)	"Climate, Supply-Demand Balance and Long-Term Grid" Programme/ "Grid Evolution" Roadmap "Climate, Supply-Demand Balance and Long-Term Grid" Programme/ "Decarbonisation, Electrification and Consumption Flexibilities" Roadmap "Climate, Supply-Demand Balance and Long-Term Grid" Programme/"Long-Term Supply-Demand Modelling" Roadmap
▸ Propose new methods for calculating hosting capacity for different types of customers (batteries, consumption, etc.) that take into account various contractual conditions (e.g., number of hours of operational limitation) and facilitate the automation of calculations to increase their volume and frequency. These methods must also ensure calculation of robustness (notably regarding the order of arrival of actors) and consistency with the methods used for network development planning.	Formalisation, proof of concept and demonstration of a minimum viable method to assist connection planning (with a prospective pilot case study corresponding to battery connections).	"Climate, Supply-Demand Balance and Long-Term Grid" Programme/"Grid Evolution" Roadmap

Optimisation of asset management policies using reliability and decision theories that take risks into account

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Continue the design and dissemination of methods and tools enabling the optimisation of asset management based on risk and reliability assessments, with particular attention to modelling the consequences on the service provided and the consistent quantification of residual industrial and operational risks. ▸ Participate, within standardisation groups, in the standardisation of asset management methods based on reliability theory to reinforce their robustness (scientific rigor and operational relevance). ▸ Identify the required changes in maintenance policies to take into account the capabilities and knowledge provided by the aforementioned tools and develop the methods necessary for the evolution of these policies.	After achieving TRL 7 (industrial-scale demonstration) for measurement and power transformers during TURPE 6, the new step in TURPE 7 is to move from the individual asset to the asset system (achieving TRLs 5, 6 and 7 in TURPE 7 – i.e., concept validation and demonstration).	"Asset Management" Programme/"Asset Management Support Systems (SAGA)" Roadmap
▸ Develop physical and statistical aging models of assets, focusing on the conductors-supports-foundations system of overhead lines, as well as on underground and submarine cables; then validate the robustness of these physical models through laboratory testing and build the necessary databases for diagnostics (non-destructive testing to better guide renewal and maintenance actions). ▸ Design, prototype and experiment with digital tools for simulation and diagnostics of transformer asset conditions to support decision-making on maintenance actions based on criteria of optimality and priority.	Following the achievement of TRL 7 for the initial aging models of overhead cables during TURPE 6, the activity will be redirected and strengthened to model the conductor-support-foundation system of overhead lines, underground cables (achieving TRLs 4, 5, 6 and 7 in TURPE 7), and submarine cables (achieving TRLs 3 and 4). Achievement of TRL 7 for "quick wins" related to SF6 and air coolants undertaken during TURPE 6, and achievement of TRLs 4 and 5 for the numerical modelling of transformers.	"Asset Management" Programme/ "Modelling, Assessing and Predicting Asset Behaviour" Roadmap
▸ Refine the integration between the methods and tools used for asset management support and those used for power flow constraint studies, in order to better account for the mutual interactions between the two processes (modelling the impact of maintenance on network availability, modelling the network's value of use for optimising maintenance decisions, assisting in the optimal placement of outages considering system risks and implementation constraints), with particular attention to modelling the consequences on service delivery and the consistent quantification of residual industrial and operational risks.	Formalisation, proof of concept, and demonstration of methods enabling the co-optimisation of asset renewal and engineering (achievement of TRLs 5, 6, 7) and improvement of outage optimisation methods developed during TURPE 6.	"Asset Management" Programme/"Asset Management Support Systems (SAGA)" Roadmap "Climate, Supply-Demand Balance and Long-Term Network" Programme/"Network Evolution" Roadmap

A2. Support the operational performance of maintenance through enhanced network inspection and asset condition diagnostics

In a context of aging assets and increased climatic constraints, maintenance activities are essential to preserve the reliability, availability, and safety of the network infrastructure. For example, monitoring the geometric proximities between overhead lines and the environment is indispensable, particularly to manage the risk of electrical arcing with vegetation, which can not only compromise the quality of electrical supply to customers but also cause wildfires during dry conditions. Automated detection of non-immediate-impact anomalies within network components can enable repair planning according to their priority, preventing the occurrence of unforeseen incidents that could lead to power outages, while also reducing preventive equipment replacements.

Beyond the aging of infrastructure, the simultaneous growth in required resources (human and budgetary) to rapidly adapt the network to future needs risks putting pressure on RTE's capacity to both carry out and finance its engineering and maintenance activities. It is therefore advisable to seek new solutions to improve the performance of maintenance activities and thus alleviate these resource constraints. Recent advances in multiple technologies (IoT, artificial intelligence, robotics, satellite imaging, digitisation) open up promising new possibilities for automation, information processing, and decision support. However, it remains necessary to design and demonstrate the techno-economic relevance of new systems based on these technologies for use cases related to the maintenance of electricity transmission infrastructure.

The 2025-2028 R&D Plan aims to address this "A2" objective through work in the following area:

Automatic inspection and intervention support

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Demonstrate systems for infrastructure inspection that integrate, in a modular and interoperable way, carriers (drones, robots, helicopters), sensors (cameras, lidar) and information processing algorithms (artificial intelligence). ▸ Demonstrate measurement, monitoring and alert systems for proximity to infrastructures (vegetation, construction sites, landslides) using satellite imagery.	Achievement of TRLs 5, 6, and 7 for minimum viable products (vector-sensor-AI) related to linear and substation infrastructures. Achievement of TRLs 6 and 7 for proximity management systems based on satellite imagery.	"Asset Management" Programme/"Network Inspection Automation and Intervention Means Modernisation" Roadmap

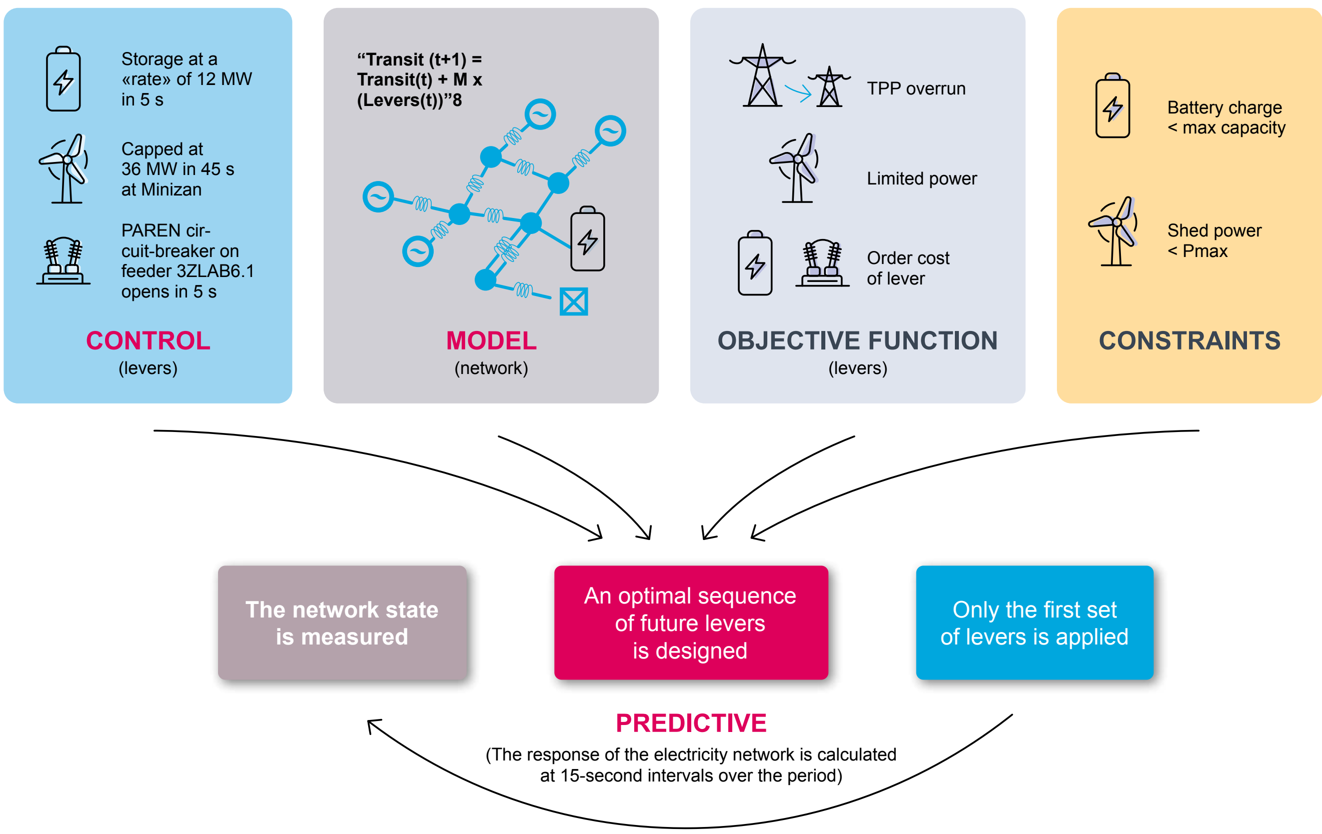
A3. Design and deploy new infrastructure solutions to facilitate and accelerate the grid's adaptation to future uses

The investment trajectories outlined in France's network development plan (SDDR) for the 2025-2040 period present a major challenge in accelerating the pace of project execution. Difficulties are anticipated at multiple levels, such as the availability of skilled labour, the capacities of supply chains and subcontracting, and administrative and organisational timelines.

These difficulties are compounded by uncertainties regarding the development dynamics of energy uses and generation technologies, as well as their precise locations, within timeframes compatible with the development periods of network infrastructures.

To better manage these risks, it will be essential for RTE to have at its disposal a maximum number of agility levers to reduce the need for heavy and long-term investments, shorten implementation timelines, simplify processes, be able to redirect projects or reconfigure existing infrastructures and have temporary interim solutions while awaiting the completion of structural investments.

For example, preliminary results from studies conducted as part of the SDDR reveal that beyond the benefits brought by existing automation solutions (NAZA devices: New Adaptive Zone Automata), approximately 2 to 3 billion euros in network infrastructure investments could be avoided by 2040, provided that real-time congestion management support solutions are available, particularly for the HTB2 voltage networks, where congestion is generated notably by the growth of renewable energy production. Such solutions would likely consist of a combination of automation systems and tools enabling situation analysis followed by rapid decision-making by operators at the Electrical System Operational Centres (COSE).



The 2025-2028 R&D Plan aims to address this “A3” objective through work in five areas:

Architecture of automation systems and new system control functionalities

Consistency	Targeted achievements under TURPE 7	“Programmes”/ “Roadmaps” contributing to the ambition
▸ On one hand, design an architecture for automation systems based on principles of modularity, scalability, interoperability, and robustness/resilience to more effectively address a variety of application contexts and facilitate their widespread deployment across the network while ensuring operational consistency and long-term maintainability; and on the other hand, develop a simulation platform for the operation of these systems within their environment – intertwining the electrical grid and digital infrastructures – thus enabling the assessment of the integrated proper functioning of the automation systems and the validation of their robustness and resilience properties. ▸ Design new automation systems to expand the range of tools available to increase transmission capacity – either on a lasting basis to reduce the need for major capital investments, or temporarily in anticipation of structural investments that are necessary but take longer to implement.	Following development in TURPE 6, from proof of concept to industrial deployment, of the core computing units of the NAZA automation systems, development of a simulation platform for validation and qualification of the proper functioning and robustness of the automata within the integrated cyber-physical environment (achievement of TRLs 5 to 7), and demonstration of new algorithms for use cases not covered by NAZA (*i.e.*, constraint management). HTB2-HTB3, tension constraint management	“Future Cyber-Physical and Eco-Designed Network Infrastructure Programme”/ “Roadmap for Hybrid Cyber-Physical System Control Architecture”

Virtualised substation protection and automation systems

Consistency	Targeted achievements under TURPE 7	“Programmes”/ “Roadmaps” contributing to the ambition
▸ Continue collaborations to demonstrate and qualify virtualised protection, automation and control (vPAC) systems, confirming their economic profitability (OPEX and CAPEX) as well as the agility gains for reconfiguring or adapting protection systems according to the evolution of connected client installations.	After proof of concept in TURPE 6, field demonstration of a multi-vendor virtualised protection, automation and control system (achievement of TRLs 5, 6 and 7) and analysis of the techno-economic conditions for successful industrialisation by the end of TURPE 7.	“Future Cyber-Physical and Eco-Designed Network Infrastructure” Programme/ “Substation-Automation Virtualisation” Roadmap

Interoperable high-voltage direct current (HVDC) technologies among themselves and with the alternating current (AC) grid

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Promote, through R&D collaboration, the emergence of interoperable high-voltage direct current (HVDC) technologies both among themselves and with the alternating current (AC) grid, enabling meshing for optimised pooling of connections and better integration into the existing network.	Completion of the interOPERA project (demonstration of the simulation platform for testing the interoperability of replicas, *i.e.*, achievement of TRL 7), transfer of results to standardisation, experimentation with new types of converters on the platform; stability study of meshed HVAC/ HVDC hybrid networks, particularly in the presence of converters operating in grid-forming mode.	"Voltage, Protection, Stability" Programme/ "Power Electronics and Direct Current" Roadmap

Notes : These efforts benefit from collaborative support and institutional funding within the framework of the Horizon Europe interOPERA project.

New technologies for transmission lines and substations

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Continue and strengthen involvement in standardisation working groups related to the performance, interoperability and eco-design of electrical network equipment, in order to promote the development of qualified products that comply with regulations and best meet the future needs of the Public Transmission Network. ▸ Maintain a minimal level of monitoring, preliminary study, and qualification activities for new terrestrial power transmission line and substation technologies that enable productivity gains and reduced implementation time.	Standing study activity and support for standardisation regarding issues related to the performance, interoperability and eco-design of terrestrial electrical network equipment.	"Asset Management Programme/Roadmap: Modelling, Assessing and Predicting Asset Behaviour" "PRISME Programme: Partnerships, Valorisation, Transformation and Cross-Programme Strategies/Roadmap: Standardisation"

Network acceptance		
Consistency	**Targeted achievements under TURPE 7**	**“Programmes”/ “Roadmaps” contributing to the ambition**
•Understand the drivers of society’s relationship with energy and the grid in order to identify factors conducive to the acceptance of RTE infrastructures (notably overhead and maritime) and to experiment with new practices (e.g., landscape approaches, measures favourable to biodiversity).	Completion of exploratory studies identifying biodiversity factors and societal relationships conducive to the acceptance of terrestrial, overhead and maritime infrastructures.	“Environment, Society and Foresight” Programme/ “Energy, Grid and Society” Roadmap “Environment, Society and Foresight” programme/ “Regenerative Lines” Roadmap

A4. Explore and validate design options for connecting deep offshore wind power to the grid

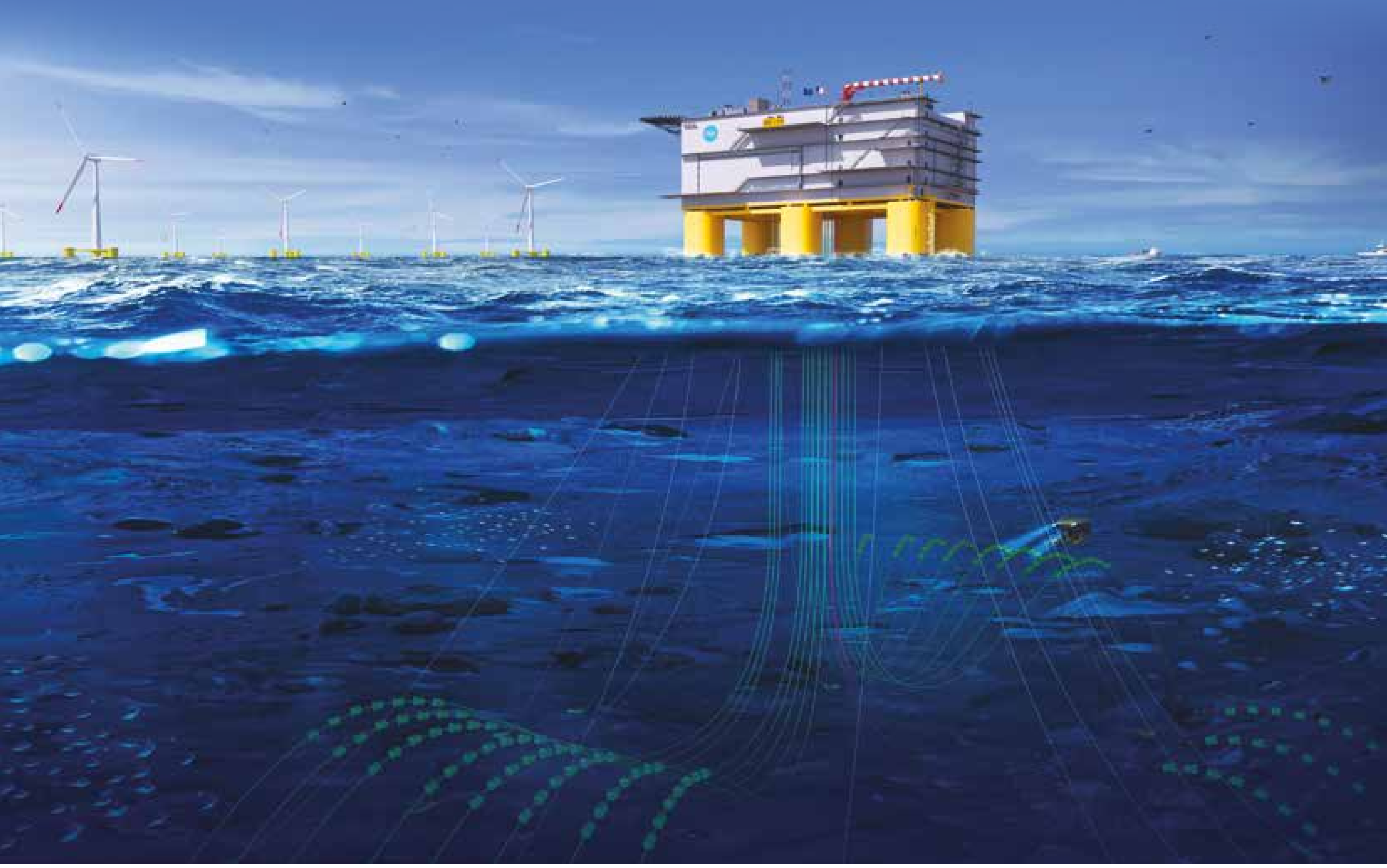
The French energy and climate strategy project sets a target of 45 GW for offshore wind power by 2050. This target lies in the middle of the scenarios studied in the Energy Futures Pathways to 2050.

To specify the development areas for future offshore wind farms ahead of the third Multiannual Energy Plan (PPE 3), a public debate was held along the four maritime façades of mainland France from 20 November 2023 to 26 April 2024 under the authority of the National Commission for Public Debate (CNDP). The debate addressed issues related to the future of the sea, the coastline, marine biodiversity and offshore wind energy. Its main objective was to plan priority project zones to be allocated within the framework of PPE 3, as well as to pre-identify potentially larger areas for longer-term projects (between 2040 and 2050). At least three identified maritime zones are located at depths exceeding 100 meters and could therefore involve connections using floating substations and dynamic cables.

For reference, following the public debates held in 2020 and 2021 – which revealed strong public concern regarding the visual impact of future offshore wind farms – the decision was made to locate the offshore wind farms of phases AO4 and AO5 more than 40 to 50 kilometres from the coast.

The desire to locate the wind farms further offshore, combined with the need to consolidate grid connections in response to the expected growth dynamics of offshore wind energy by 2050, encourages prioritising high-capacity high-voltage direct current (HVDC) connection solutions (1 to 2 GW), which offer a better cost-benefit for society. Moreover, the rapidly increasing depth of the seabed in most of the identified suitable areas necessitates the use of floating structures, given the current and prospective knowledge on offshore platform construction techniques.

The connection cost for 6 to 8 gigawatts of offshore wind using HVDC technology on floating platforms could, according to prospective estimates, represent an investment cost of around ten billion euros.



However, this design of floating high-voltage direct current (HVDC) connection infrastructure has never been implemented to date. It involves technical feasibility and operational durability risks that require thorough studies. The uncertainties concern three major components of such installations:

- The HVDC converters, subjected to oscillations and shocks of the platforms (and resulting mechanical stresses).
- The alternating current transmission equipment (GIS, transformers), subjected to oscillations and shocks of the platforms (and resulting mechanical stresses).
- The “dynamic” cables connecting the platforms (which move with tides, waves, winds, and currents) to the conventional submarine cables (anchored to the seabed).

In addition to overcoming the aforementioned technical challenges, the goal will also be, through collaborative approaches, to promote the development of industrial sectors necessary for the execution of such projects and for the maintenance of the installations.

Furthermore, alternative connection technologies could develop over the next decade. For example, connections via substations installed at great depths could constitute an alternative to floating solutions. Additionally, although currently at a low level of maturity, the emergence of long-distance superconducting submarine cables would allow the transmission of considerable electrical power over a limited number of conductors, while avoiding the need for costly and complex-to-maintain offshore HVDC stations.

The 2025-2028 R&D Plan aims to meet this “A4” objective through work in two areas:

RHODE Project (ADEME/France 2030 initiative): identify and overcome the technological barriers of floating connections (floaters, dynamic cables, onboard power electronics).

Consistency	Targeted achievements under TURPE 7	“Programmes”/ “Roadmaps” contributing to the ambition
▸ Summarise the theoretical studies conducted during the TURPE 6 period (notably “AFOSS DC”) to model the phenomena affecting the floaters, dynamic cables and onboard power electronics, and to study their theoretical long-term behaviour. ▸ Specify and conduct a basin experiment to confirm the dynamic behaviour of the floaters and validate the results of previous theoretical studies. ▸ Test, onshore but physically simulating the sea conditions of a floating platform (using vibration tables), certain sensitive electrical equipment to verify their suitability for the floating marine environment (dynamic cables, onboard HVDC equipment), with the aim of refining design choices and obtaining initial feedback before committing to full-scale infrastructure, notably ensuring their long-term operability (maintenance operations, component replacement). (*) ▸ Propose industrial guidelines for the connection of offshore wind requiring the deployment of floating electrical platforms, based on the findings of the studies and experiments conducted, the techno-economic evaluation of the options considered and the assessment of residual technological risks.	Achievement of TRLs 3, 4 and 5 (with the objective of confirming technical feasibility and operational durability conditions before 2029).	“Future Cyber-Physical and Eco-Designed Network Infrastructure” Programme/“Maritime” Roadmap

Notes: These works should largely be carried out within the framework of a consortium applying for France 2030 funding.

* Sea tests using buoys are also planned to study the behaviour of dynamic cables. These tests will be confirmed depending on budgets and the support of European countries contributing to this research effort.

Complementary and synthesis studies for the connection of deep offshore wind power		
Consistency	**Targeted achievements under TURPE 7**	**"Programmes"/ "Roadmaps" contributing to the ambition**
•Conduct the techno-economic study of fixed substations installed at depths of around one hundred meters as an alternative to floating connection solutions •Monitor offshore connection technologies using superconducting AC cables. •Contribute to the study and demonstration of an innovative solution for mitigating noise pollution generated during construction activities (piling/drilling for foundation piles and anchor installation). •Propose industrial guidelines for the connection of offshore wind power in seabed exceeding one hundred meters in depth, based on lessons learned from previously described projects, complementary techno-economic studies and monitoring, the techno-economic assessment of the options considered, and the evaluation of residual technological risks.	Following an initial exploration and project development phase under TURPE 6, exploratory activities (technology monitoring, partnership building, desk studies) will be reduced to a strict minimum; a synthesis report will be produced.	Programme: "Cyber-Physical and Eco-Designed Futures of Grid Infrastructures"/ "Maritime" Roadmap

2.3 Contribute to the transformation of the operation and management of the electrical system

Three R&D objectives should guide the R&D roadmap under TURPE 7 to support the proper adaptation of the processes and mechanisms ensuring the operational functioning of the electrical system, while guaranteeing continuity of supply and power quality:

B1. Support the operational performance of power system management through decision-support tools and automation.

B2. Preserve the system's operational reliability by transforming the mechanisms required to maintain grid stability and electricity quality in the face of growing decentralised generation, new types of consumption and power electronics-based conversion interfaces.

B3. Facilitate system balancing through structural modulation of energy uses, flexibility services and the upgrade of backup mechanisms.

B1. Support the operational performance of power system operation through decision-support tools and automation

The principles governing the operation of the power system are becoming increasingly complex, with growing uncertainties regarding power injections, greater variability in power flows both at the local and pan-European levels, more complex interactions with distribution networks, and the massive integration of inverted based resources (IBR) and power-electronics based conversion interfaces (used for grid connection of generation and load sites, and HVDC lines). These interfaces exhibit less "linear" behaviour compared to traditional grid components and do not inherently provide the stabilising and self-regulating effects of the latter – such as the mechanical inertia of synchronous generators and the voltage- and frequency-sensitivity of conventional loads.

In parallel, the grid control architecture is evolving to incorporate more distributed automation within the system, with the dual objective of increasing the network's capacity to accommodate new uses and leveraging advanced automation to manage certain operational contingencies, particularly those occurring on very short time scales.

Operators of the Electrical System Operations Centres (COSE) are thus faced with an increasingly complex cyber-physical system of systems. Given the potential consequences of large-scale incidents, grid operation procedures generally follow a precautionary principle when dealing with unmanaged complexities: operational security margins must be maintained to mitigate the risk of uncontrolled system evolution. Furthermore, misjudgements regarding the actual state of the grid can lead to suboptimal or even counterproductive decisions, such as the unnecessary activation of the system or balancing services.

To enable operators to better grasp the growing complexity of the system – and thereby reduce the required operational security margins – it is necessary to equip power system control rooms with new hyper vision and decision-support tools (intelligent assistants, various analysis and simulation tools). These tools should facilitate the identification and implementation of optimal system operation trajectories, taking into account stability and power quality criteria, uncertainties across different time horizons and the available corrective actions. For example, security analysis

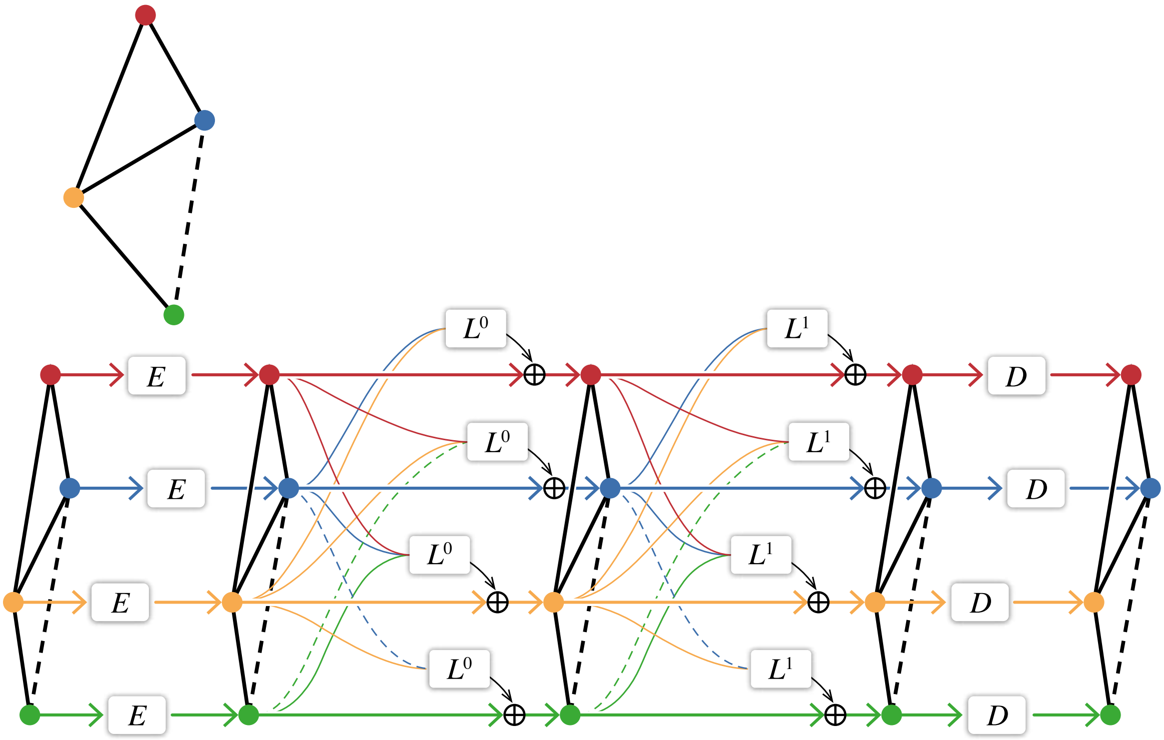


FIGURE Graph Neural Networks pour la conduite du réseau

algorithms using optimisation under uncertainty methods can provide valuable support in determining available transfer capacities in the presence of uncertain injections and withdrawals, as well as available levers (such as network topology adjustments, phase-shifting transformer tap changes or modulation of injections) to manage operational contingencies.

The stakes are high, as projections from the SDDR indicate a rise in residual congestion costs that could reach several hundred million euros per year between 2030 and 2040 – approximately €450 million per year by 2035 in a scenario consistent with the draft PPE 3, which is four to five times higher than current levels. By deploying tools that enable a 5% to 10% reduction in congestion volumes through the moderation of required operational security margins, the potential savings could range from €20 million to €50 million per year.

In addition, systems for the qualification and operational coordination of distributed automation within the power system are necessary to ensure overall consistency and to prevent local automated actions from generating additional operational costs due to conflicting responses.

For example, preliminary results from studies conducted within France's network development plan (SDDR) framework reveal that beyond the benefits provided by existing NAZA solutions, approximately €2 to 3 billion in network infrastructure investments could be avoided by 2040, provided that real-time congestion management tools are available, particularly for congestions generated on the HTB2 voltage networks due to the growth of renewable generation. Such solutions would likely not only consist of new automation systems developed under objective A4 but also include tools enabling COSE operators to promptly analyse the evolving operational situation and make appropriate decisions while considering the effects of distributed automation.

However, all this future tooling comes with a drawback: its complexity is also expected to increase compared to traditional grid operation tools. Consequently, a critical success factor will be the ability to manage this dual complexity (the complexity of both the power system and the tools used to control it) at various stages – from prototyping, validation and deployment of the tools to operator training and ensuring that system operation remains controlled in the face of diverse events and plausible scenarios.

The challenges of mastering this are multiple. Effective handling of the tools by operators will be essential to realise the expected benefits and even to avoid degrading operational performance due to misinterpretation of information. Since these tools are developed and improved progressively and incrementally, it will be necessary to have the capability to experiment with, validate and rapidly integrate new components within an existing suite of tools. Finally, the scale and pace of transformation expected in the power system will make it increasingly difficult for operators to rely solely on past experience and on-the-job learning. Therefore, beyond the methods and tools deployed in an operational context, RTE faces a growing need for an "electric system operation laboratory" to accelerate solution deployment and ensure operator training, serving three main purposes:

- An R&D experimentation and proof-of-concept platform to test the system integration of prototype tools for the control room, thereby "designing" new ranges of decision-support tools while ensuring coherence, fluidity, ergonomics and reliability of interactions between the operator and multiple assistants.
- A controlled demonstration environment to test and validate new tools prior to industrial deployment, in combination with the existing suite of operational tools.
- A prototype infrastructure to develop and test new operator training practices, exercises for responding to a variety of complex operational situations, and studies of cyber-physical incident scenarios.

The 2025-2028 R&D Plan aims to address this "B1" objective through work in five areas:

Short-term forecasting methods and tools for injections and withdrawals		
Consistency	**Targeted achievements under TURPE 7**	**"Programmes"/ "Roadmaps" contributing to the ambition**
•Design, prototype and experiment with improvements to generation and demand forecasting tools for injections and withdrawals to adapt them to the evolving generation-consumption mix and local granularity needs, with a particular focus on integrating exogenous information provided by stakeholders, modelling modulation behaviours in response to market signals (and other flexibility behaviours), enhancing performance through hybridisation techniques combining physical models and artificial intelligence, as well as characterising the uncertainties associated with forecasts.	Achievement of TRLs 5, 6 and 7 for a minimum viable tooling adapted to the 2030 mix.	"Short-Term Forecasting and Short-Term EOD" Programme/"Short-Term Forecasting" Roadmap.

Support methods and tools for managing supply-demand balance

Consistency	Targeted achievements under TURPE 7	“Programmes”/ “Roadmaps” contributing to the ambition
Design, prototype, and experiment with solutions to support supply-demand balance management within a shortened operational window, taking into account network capabilities amid increasing uncertainties, with a particular focus on modelling risks and consequences related to supply-demand balance in 2030, studying and simulating balancing and incentive strategies, assisting in reserve optimisation, and characterising the impacts of automation systems.	Achievement of TRLs 4, 5 and 6 for minimum viable methods and tools adapted to 2030.	”Short-Term Forecasting and Short-Term EOD” Programme/“Short-Term EOD” Roadmap

Security analysis and support methods and tools for managing power flows and voltages

Consistency	Targeted achievements under TURPE 7	“Programmes”/ “Roadmaps” contributing to the ambition
Design, prototype, and experiment with new solutions for network operational security analysis and decision support, based on state-of-the-art scientific techniques[5], enabling the modelling of network operational complexities, temporal dynamics, uncertainties, and the curative action capabilities provided by various flexibility levers and proposing to operators the preventive actions necessary for proper network operation.	Achievement of TRLs 4, 5, 6 and part of 7, for minimum viable methods and tools adapted to 2030.	“System Control” Programme/“Flow Control” Roadmap “Voltage, Protection, Stability” Programme/ “Voltage” Roadmap
Design, prototype, and experiment with artificial intelligence solutions to focus operators’ attention and reduce their workload (hypervision, automation support, complex alarms and explanatory elements).	Achievement of TRLs 4, 5, 6 and 7 for minimum viable methods and tools adapted to 2030.	“System Control” Programme/“Interactive Smart Cockpit” Roadmap

5. Numerical simulation artificial intelligence, robust optimisation, hybridisation of optimisation methods and machine learning, …

Coordination and optimisation of automation systems

Consistency	Targeted achievements under TURPE 7	“Programmes”/ “Roadmaps” contributing to the ambition
▸ Develop an overall architecture and design an orchestration system that integrates the various decision support modules and distributed automations coherently, coordinately, robustly and efficiently to deliver system control capabilities that meet performance and operational security requirements.	Achievement of TRLs 4, 5 and 6 to enable industrialisation by 2030.	“System Control” Programme/ “Flow Management” Roadmap. “Cyber-Physical and Eco-Designed Futures of Grid Infrastructures” Programme/“Control Architecture of the Hybrid Cyber-Physical System” Roadmap “PRISME: Partnerships, Valorisation, Transformation, and Cross-Programme Strategies” Programme/ “Cross-Programme Strategy for Decision Support Tools” Roadmap

Laboratoire de la conduite du système électrique

Consistency	Targeted achievements under TURPE 7	“Programmes”/ “Roadmaps” contributing to the ambition
▸ Assemble an experimental and representative operator environment, including the human-machine interfaces of the control room and the decision-support assistants and tools used for system operation, including new tools and interfaces to be tested or validated. ▸ Develop, notably within the framework of the Horizon Europe TwinEU project, a “digital twin” – that is, a simulator of the cyber-physical system capable of replicating its overall behaviour by modelling the electrotechnical components of the power grid, the automation, protection and control systems, telecommunications networks, and more. ▸ Design a “game master” to generate scenarios, drive the digital twin according to these scenarios while accounting for interactions with the operator and produce evaluation metrics on system operation performance.	Achievement of TRLs 4, 5 and 6, addressing the need for an R&D experimentation and proof-of-concept platform by 2028 and enabling industrialisation for training purposes by 2030.	PRISME Programme: Partnerships, Valorisation, Transformation and Cross-Programme Strategies”/Roadmap: “Cross-Programme Strategy for Decision Support Tools System Control Programme”/ “Flow Control Roadmap Network Stability Control and Simulation Programme”/ “Electrotechnical Simulators for System Operation

Notes: These efforts will benefit from collaborative levers and institutional funding within the framework of the Horizon Europe TwinEU project.

N.B.: Given the multiplicity of use cases and in order to increase future capitalisation opportunities, the previous activities will be guided by the following principles:
- Conduct opportunity studies to assess, in advance, the potential benefits (economic, environmental, operational) and success conditions of automation and decision-support concepts for high-stakes use cases.
- Architect modular and scalable solutions for the various mentioned assistants, relying on the concepts of digital twins, standards, ontologies, hybridisation between physical models and artificial intelligence, and open-source software commons.

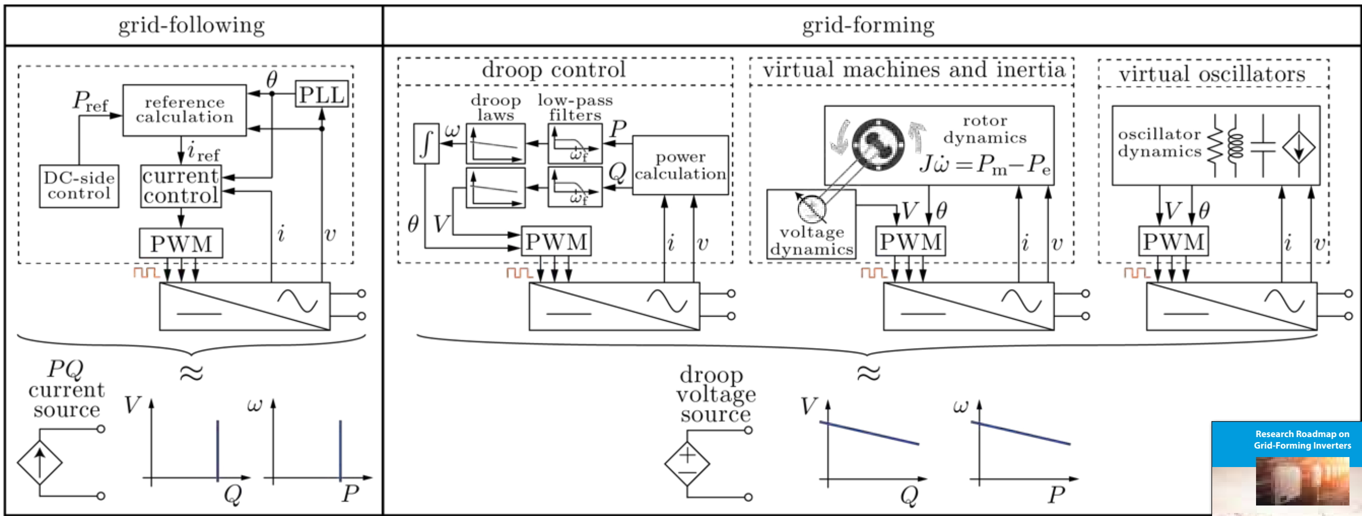
B2. Preserve the operational reliability of the system: transform the necessary mechanisms to maintain the stability and quality of the electricity network in the face of the expansion of decentralised generation, new types of consumption and power electronics-based conversion interfaces

The devices currently ensuring stable network operation with high power quality were designed in the context of centralised generation, consisting mainly of synchronous rotating machines connected primarily to high and extra-high voltage networks. For example, voltage is maintained relying on power plants connected to the transmission network that participate in voltage regulation mechanisms. This voltage is then transmitted to the distribution and sub-transmission networks through load regulation devices and reactive power compensation systems. The rapid growth of decentralised renewable generation, connected to distribution and sub-transmission networks, disrupts these principles.

Furthermore, the widespread deployment of power electronics throughout the system – at the generation, consumption and HVDC transmission infrastructure levels – is progressively altering the electrotechnical behaviour of the network, ultimately jeopardising the effectiveness of the devices that currently ensure its proper operation and security (dynamic stability, protection and defence schemes, compliance with power quality criteria, notably voltage quality).

The development of new grid-interfaced applications using power electronic converters, such as electric vehicle charging stations, data centres (cloud computing) and decarbonised industrial sectors (notably electrolysers), intensifies these disruptions and raises questions about the adequacy of connection requirements and other regulatory and normative provisions for these new types of electricity customers.

FIGURE Functional diagrams of grid-following and gris-forming inverters. Grid-following inverters mimic current sources at their output terminals, Whereas grid-forming inverters act like voltage sources whose output abides by droop laws.



Source : Research Roadmap on Grid-Forming Inverters.

Furthermore, the proliferation of HVDC infrastructures driven by the development of interconnections and offshore wind power leads to a gradual AC/DC hybridisation of the transmission grid mesh, featuring fundamentally different characteristics between these two categories of assets (electrotechnical behaviour and controllability).

Finally, the aforementioned transformations particularly impact the operation of distribution networks and require rethinking the interface between the transmission system operator (TSO) and the distribution system operator (DSO) to ensure coherent and coordinated management of system services.

The 2025-2028 R&D Plan aims to address this “B2” objective through work in five areas:

Understanding of phenomena and modelling

Consistency	Targeted achievements under TURPE 7	“Programmes”/ “Roadmaps” contributing to the ambition
• Develop a consolidated understanding of the impacts of widespread deployment of power electronics converters and digital automation systems on the electrotechnical behaviour of networks, by analysing all the devices that ensure the foundations of the electrical system (dynamic stability, protection and defence schemes, compliance with electricity quality criteria, notably voltage quality). • Develop numerical models of power converters and digital automation and protection systems suitable for electrical system simulators, taking into particular account the greater diversity in the physical and logical principles governing the behaviour of these new devices (compared to traditional loads and synchronous machines). • Improve or develop the integration of these system phenomena into methods and tools for network studies (ranging from infrastructure development studies to operational strategy studies) in order to anticipate necessary adaptations of devices.	Incremental improvement of methods and tools from the formulation of new phenomena to prototyping and then full-scale experimentation (TRLs 2 to 7). Conducting pilot studies.	“Grid Stability Control and Simulation”/ “Stability of a Rapidly Changing System” Programme “Grid Stability Control and Simulation”/ “Electrotechnical Simulators of System Operation” Programme “Voltage, Protection, Stability” Programme/ “Protections” Roadmap

Analysis and adaptation of the control architecture

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Identify and implement adaptations to the system control architecture to preserve the proper electrotechnical operation of the system (dynamic stability, protection and defence schemes, compliance with power and electricity system.		"Cyber-Physical and Eco-Designed Future Network Infrastructures" Programme/ "Control Architecture for the Hybrid Cyber-Physical System" Roadmap "Voltage, Protection, Stability" Programme/ "Voltage" Roadmap "Voltage, Protection, Stability" Programme/ "Protections" Roadmap

Observability of dynamic behaviour

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Study the needs for improving the observability of the network's dynamic behaviour through high-precision measurement devices[6], for understanding and controlling new instability phenomena, validating simulation models and performing post-event analysis of instability incidents. ▸ Develop and then experiment with the corresponding digital methods and tools for operational monitoring and post-event analysis.	Achievement of TRLs 4, 5, and 6.	"Control and Simulation of Grid Stability"/ "Stability of a Rapidly Changing System" Programme

6. Devices such as PMUs (Phasor Measurement Units) that measure voltage and current amplitudes and phases with high-frequency sampling on the order of a few milliseconds. These measurements are precisely synchronised, most often using a GPS clock, which is essential for activities such as feedback analysis or the study of oscillation modes in the power system.

Specification of system services for converters (grid forming, voltage)

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Explore, based on techno-economic analyses, regulatory or normative adjustments that could effectively contribute to preserving the safe operation of the system (such as the requirement for devices operating in "grid-forming" mode, for example).	Completion of studies and experiments to define and justify the characteristics of system services (including grid forming) that should be required from converters by 2030.	"Control and Simulation of Grid Stability"/ "Stability of a Rapidly Evolving System" Programme "Voltage, Protection, Stability" Programme/ "Power Electronics and Direct Current" Roadmap

Voltage coordination testing at the TSO-DSO interface

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Design, prototype and test in an operational environment, in collaboration with DSOs, coherent and coordinated mechanisms for managing system services at the interface between the transmission and distribution networks.	As part of a collaboration between RTE and Gérédis, demonstrate through a techno-economic study the operational benefits of a coordinated dynamic management of reactive power setpoints, involving various levers (generation sites, STATCOM equipment at primary substations), and validate the results and feasibility through a demonstration in a test or even operational environment (achievement of TRLs 4, 5, 6).	"Voltage, Protection, Stability" Programme/ "Voltage" Roadmap

Notes: The realisation of a full-scale demonstrator will likely require additional funding beyond the incentive regulation for R&D under TURPE. The corresponding financing plans will be defined as part of the aforementioned preliminary studies.

B3. Facilitate system balance through structural modulation of usage, flexibility services and the renovation of protection devices

As outlined in the 2023 Forecast Report, the French and European commitments to massive decarbonisation of energy uses (transport, industry), in response to the climate challenge, combined with strategic economic issues of reindustrialisation and development of the digital sector, require preparing for a significant growth in electricity consumption. At the same time, the development of production capacity to meet these new demands faces tough challenges (technological, social acceptance, financing, industrial capacity). A key lever to mitigate potential recurrent supply-demand balance tensions in an unfavourable scenario of poor production availability will be the ability to massively modulate consumption.

Thus, the 2023 Forecast Report presents various possible flexibility portfolios, including, for example, a median trajectory that would ensure by 2035 that 15 million consumers have access to tariff offers incentivising usage flexibility, 300,000 buildings larger than 1,000 m² are equipped with technical management systems (BMS), 12 to 27 million charging stations enable load control and industrial load shedding capacity increases to 4 GW.

To achieve this, the future French electrical system will need to integrate, within about ten years, mechanisms enabling the massive, reliable and generic modulation of electrical usage. By usage modulation, we specifically mean the ability to modify consumption and local generation behaviours – whether regularly, through structural tariff incentives or automatic energy optimisation, or in the form of dynamic flexibility services activated upon request by a market participant or a network operator – to contribute to optimising a portfolio of market transactions, balancing supply and demand on the grid or supporting system protection during imbalances between supply and demand. Electrical usage notably includes residential, commercial, and industrial consumption (including electric mobility) as well as residential and commercial photovoltaic electricity production. The terms "massive, reliable and generic" refer to designing mechanisms that allow services to scale rapidly to hundreds of thousands or even millions of sites, without operational management generating prohibitive complexity or costs, while ensuring control over service quality and fully addressing the associated cybersecurity requirements.

In hindsight, over the past decades, the development of flexibility services has proven slow and arduous. In some segments (notably residential), there has even been a decline. The reality on the ground is therefore significantly misaligned with expectations, whether those expressed at the European level through initiatives such as the European Commission's "Digital Transition of the Energy System" communication, or those revealed by the supply tension period that France experienced in 2022-2023.

One of the barriers to development appears to lie in the fragmentation of the ecosystem. This fragmentation undermines the economies of scale required for unit gains to significantly exceed costs, complicates systematic approaches and creates an entry cost for the consumer. To address this fragmentation, an interoperability framework is needed that enables the development of flexibility systems in a generic way, robust to changes in electricity supplier, location (residential, commercial) or equipment provider. Indeed, scaling up will be difficult with "custom-made" devices requiring multiple adaptation efforts (and costs) throughout the lifecycle of a consumption site. A simplicity comparable to historical mechanisms such as EJP, TEMPO, or day/night pricing should be sought.

Furthermore, the incentive for flexibility could arise from considerations beyond merely optimising the electricity bill. Carbon footprint management appears to be an increasing concern among consumers (both businesses and individuals). The growing correlation between signals related to supply-demand balance and the carbon intensity of the electricity mix, as carbon-intensive production expands, encourages the exploration of incentive levers other than solely price optimisation or service remuneration. While characterised by simplicity, these mechanisms must be capable of accommodating a diversity of consumer preferences in an evolving manner.

There is also the emergence of behaviours driven by local optimisation logic (individual or collective self-consumption, "vehicle-to-home"), implementing proactive usage management mechanisms. These initiatives and their underlying motivations must be taken into account and could provide valuable insights, even if they do not currently appear to meet the conditions for mass-scale development. A coherent systemic design encompassing, among other factors, the supply-demand balance state, local realities measured by smart metering systems and the contractual and transactional conditions related to supply, seems essential for flexibility and usage modulation to develop massively and effectively for the benefit of the community.

Another aspect of this topic concerns the modernisation of system balance safeguard mechanisms. Currently, these mechanisms primarily rely on a load shedding process involving staged disconnection of clusters of consumers. This approach does not allow discrimination of usages based on their value or criticality (for example, a power cut may affect a telecommunications relay antenna while a comfort heating consumption is maintained). This limited ability to discriminate makes load shedding poorly acceptable for the affected customers. An evolution toward mechanisms such as power consumption limitation devices coupled with downstream usage modulation systems beyond the meter would, for an equivalent level of disconnection depth, reduce the perceived "cost" of load shedding to the community by encouraging a larger base of consumers to forgo their least essential electrical usages.

Finally, the multi-service dimension involves couplings and interdependencies between the processes of the Transmission System Operator (TSO), Distribution System Operators (DSOs), market participants and new decentralised actors such as energy communities,

FIGURE Different types of flexibility for needs related to supply-demand balance requiring a model for operational and transactional coordination. For example, a flexibility site may be requested simultaneously to balance a market participant's portfolio, to resolve a congestion constraint on the transmission network and to maintain voltage on the distribution network. What is the techno-economic precedence rules to arbitrate between these services and the filtering mechanisms to prevent activations from causing collateral technical constraints? How should the associated information be coordinated among the stakeholders?

The 2025-2028 R&D Plan aims to address this "B3" objective through work in four areas:

Studies of Needs and Value of Flexibilities

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
- Refine the models for studying needs and valuing flexibility, taking into account the new methods of managing the supply-demand balance and decision-making constraints under uncertainty. - Understand and model the interactions between flexibility mechanisms driven by the supply-demand balance and the management of network transit constraints; analyse the conditions for the development of flexibilities that support effective network management.	Prototyping and demonstration of modelling components enabling an improved representation of flexibilities in prospective study tools for the 2030 horizon (achievement of TRLs 4, 5, 6).	"Short-Term Forecasts and Short-Term S-D" Programme/ "Short-Term S-D" Roadmap

Notes: The concepts and models developed within the framework of the activity 'Methods and Support Tools for Supply-Demand Balance Management' will also contribute to this activity.

Understanding electricity usage flexibilities and the conditions for their development

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
- Refine the understanding of diffuse electrical usages and their modulation capabilities in response to various signals (pricing, educational, during load shedding), taking into account the required implementation delays. - Identify the main motivating factors for usage of modulation and the provision of flexibility services and quantify the levels of incentives and simplicity required for mass adoption. - Identify shared interoperability components that network operators could promote to facilitate the emergence of usage control systems at consumers' premises and the development of appropriate tariff offers by suppliers (signals on the system's forecasted state, smart metering capabilities). - Study the conditions for developing flexibility services within or in alignment with supply contracts by market participants and network pricing. - Analyse the effect of current regulatory and tariff mechanisms on incentives for modulation/flexibility and identify adjustments that could enhance their potential.	Complete proof-of-concept demonstrations of the main conditions for the development of flexibilities through studies and prototyping (TRLs 3, 4, 5) and possibly transfer to the "demonstrators" activity for the subsequent TRLs (see below).	"Environment, Society and Foresight" Programme/ "Flexibility and Regulation" Roadmap "Climate, Long-Term Supply-Demand Balance and Network" Programme/ "Decarbonisation, Electrification and Consumption Flexibilities" Roadmap "PRISME: Partnerships, Valorisation, Transformation, and Cross-Programme Strategies" Programme/ "Standardisation" Roadmap

Evolution of Supply-Demand Balance Safeguard Mechanisms

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
- Outline, then develop and analyse options for renovating the system balance safeguard mechanisms (acceptance factors, interoperability components to be developed by the networks, coherence with supply and markets, and needs for regulatory and tariff adjustments).	Achievement of TRLs 2, 3, 4 (then transfer to the "demonstrator" activity for the subsequent TRLs (see below)).	"Environment, Society and Foresight" Programme/"Flexibility and Regulation" Roadmap

Démonstrateurs de flexibilité des usages électriques		
Consistency	**Targeted achievements under TURPE 7**	**“Programmes”/ “Roadmaps” contributing to the ambition**
▸ Conduct field experiments (demonstrators) to validate the technical, economic, regulatory, and contractual success conditions, guide the emergence of appropriate solutions, and promote their standardisation through open-source collaboration and standardisation.	Monitoring of the PlaneTerr project demonstrators (heat storage and electric vehicle charging) and analysis of the lessons learned. Within the framework of the RTE-Gérédis partnership, opportunity study, definition of specifications and, if applicable, implementation of a demonstrator at the scale of the Deux-Sèvres territory – Achievement of TRLs 5 and 6 (for a subset of the considered flexibility devices/services).	“Environment, Society and Foresight” Programme/ “Flexibility and Regulation” Roadmap “Climate, Long-Term Supply-Demand Balance and Network” Programme/ “Decarbonisation, Electrification and Consumption Flexibilities” Roadmap “PRISME: Partnerships, Valorisation, Transformation and Cross-Programme Strategies” Programme/ “Standardisation” Roadmap

Notes: The implementation of these demonstrators will likely require additional funding beyond the incentive regulation for R&D within the framework of TURPE. The corresponding financing plans will be defined as part of the preliminary studies mentioned.

2.4 Anticipate and take into account major exogenous risk and disruption factors

Three R&D objectives will need to guide the TURPE 7 R&D roadmap for anticipating and addressing exogenous risk and disruption factors:

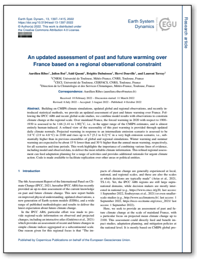
C1. Prepare the adaptation of the electrical system and infrastructure to climate change

C2. Manage industrial risks and ensure RTE's social responsibility through eco-design, circularity, and the preservation of the environment and biodiversity

C3. Anticipate risks and opportunities through prospective studies and resilience to significant uncertainties, in a context of increased instability

C1. Prepare the adaptation of the electrical system and infrastructure to climate change

At the beginning of 2023, Météo-France stated in its annual climate report[7] that "2022 was the warmest year ever recorded in France since the beginning of the 20th century." Globally, it is estimated that in 2022 the average global temperature exceeded the pre-industrial average (1850–1900) by approximately 1.15°C. At the current pace, the +1.5°C global average temperature limit set by the Paris Agreement could be reached not by the end of the century, but as early as 2035[8]. For France, the consideration of observations from recent decades leads to a significant upward revision of the possible range of temperature projections by the end of the century.


Earth Syst. Dynam., 13, 1397–1415, 2022
https://doi.org/10.5194/esd-13-1397-2022
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Earth System Dynamics

Research article

An updated assessment of past and future warming over France based on a regional observational constraint

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Received: 10 February 2022 – Discussion started: 11 March 2022
Revised: 6 July 2022 – Accepted: 3 August 2022 – Published: 4 October 2022

Abstract. Building on CMIP6 climate simulations, updated global and regional observations, and recently introduced statistical methods, we provide an updated assessment of past and future warming over France. Following the IPCC AR6 and recent global-scale studies, we combine model results with observations to constrain climate change at the regional scale. Over mainland France, the forced warming in 2020 with respect to 1900–1930 is assessed to be 1.66 [1.41 to 1.90] °C, i.e., in the upper range of the CMIP6 estimates, and is almost entirely human-induced. A refined view of the seasonality of this past warming is provided through updated daily climate normals. Projected warming in response to an intermediate emission scenario is assessed to be 3.8 °C (2.9 to 4.8 °C) in 2100 and rises up to 6.7 [5.2 to 8.2] °C in a very high emission scenario, i.e., substantially higher than in previous ensembles of global and regional simulations. Winter warming and summer warming are expected to be about 15 % lower than and 30 % higher than the annual mean warming, respectively, for all scenarios and time periods. This work highlights the importance of combining various lines of evidence, including model and observed data, to deliver the most reliable climate information. This refined regional assessment can feed adaptation planning for a range of activities and provides additional rationale for urgent climate action. Code is made available to facilitate replication over other areas or political entities.

1 Introduction

The 6th Assessment Report of the International Panel on Climate Change (IPCC, 2021, hereafter IPCC AR6) has recently provided an up-to-date assessment of the current knowledge on past and future climate change. This new report builds on improved physical understanding, updated observations, a new generation of Earth system models (ESMs), and a wide range of published methodologies and results to deliver the latest expectation about future climate change.

In the IPCC AR6, particular effort was made to provide regional-scale information on observed and projected changes, including an interactive atlas (Gutiérrez et al., 2021) which provides an assessment of recent and future changes in simple climate indices aggregated at a subcontinental scale. One reason given for this regional focus is that "The impacts of climate change are generally experienced at local, national, and regional scales, and these are also the scales at which decisions are typically made" (Arias et al., 2021, TS.1.4). Yet, the IPCC AR6 regions are still large supranational domains, while decision makers are mostly interested in national (e.g., https://www.cmcc.it/g20, last access: 1 September 2022, Soubeyroux et al., 2021) or even smaller-scale studies (e.g., http://www.acclimaterra.fr/, last access: 1 September 2022, https://reco-occitanie.org/creoc_2021/ last access: 1 September 2022).

Here, we seek to provide an assessment of past and future climate change at the scale of mainland France, with a particular focus on projected mean climate change up to 2100. This assessment could directly feed and benefit impact studies, adaptation planning, and mitigation policies at the national level. It is mostly based on CMIP6 global pro-

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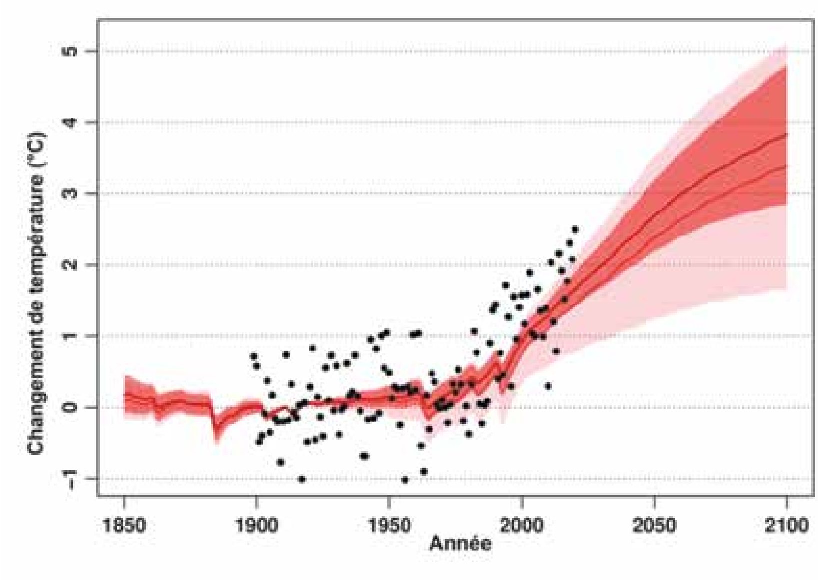


FIGURE Annual mean temperature anomalies in France relative to the 1900-1930 period in CMIP6 models, under the SSP2-4.5 scenario. See Ribes et al., 2022 – Figure 5 – for details. Taking observations into account shifts the estimate from the pink curve (unconstrained models) to the red curve (constrained model).

7. *Cf.* https://meteofrance.com/actualites-et-dossiers/actualites/2022-annee-la-plus-chaude-en-france et https://meteofrance.fr/sites/meteofrance.fr/files/files/editorial/Bilan_climatique_definitif_2022_130123_synthese_P1-23.pdf
8. https://cds.climate.copernicus.eu/cdsapp#!/software/app-c3s-global-temperature-trend-monitor?tab=app

More recently, the Copernicus consortium reported[9] that 2023 also deviated from historical norms, breaking records and approaching the 1.5°C global warming threshold relative to pre-industrial levels.

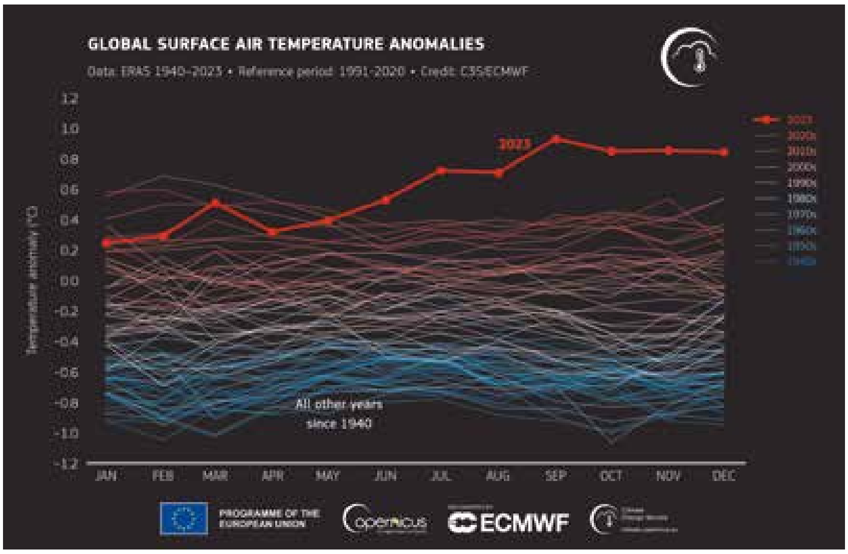


Figure: Monthly anomalies of global surface air temperature (°C) relative to the 1991-2020 period, from January 1940 to December 2023, shown as time series for each year. 2023 is represented by a thick red line, while other years are shown as thin lines shaded by decade, from blue (1940s) to brick red (2020s).

Data source: ERA5. Credit: C3S/ECMWF.

These projections, which grow more pessimistic year after year, reinforce the need to prepare the French electrical system for climate change. The underlying challenges are numerous and affect a wide range of RTE's missions:

- Climatic conditions directly affect the heating temperatures of overhead and underground conductors, and thus the maximum allowable power flows, to ensure that the excessive sag of overhead conductors does not pose a proximity risk to people or property, and that overheating of underground cables does not lead to insulation degradation and, consequently, short circuits.
- The intensification of droughts over longer periods and broader geographic areas will increase RTE's exposure to the dual risk of both being affected by and causing wildfires. On one hand, wildfire risk threatens the security of electricity supply (through the shutdown of power lines). On the other hand, faults on electrical networks that cause arcing with dry vegetation can lead to fire outbreaks with catastrophic consequences, for which RTE could be held liable – similar to PG&E in California.
- Higher operating temperatures can accelerate the aging of certain equipment and increase failure rates. Some of the equipment installed today will need to be capable of operating under the climatic conditions expected by the end of the century.
- More intense and frequent heatwaves may compromise the ability to carry out maintenance work during certain periods or require significant organisational adjustments.
- The evolution and intensification of flood risks (including surface runoff, river overflow, mudslides, rising groundwater, and coastal flooding) threaten certain existing infrastructures and will need to be considered when selecting sites for new infrastructures.

9. https://climate.copernicus.eu/global-climate-highlights-2023

- Climate change will directly affect certain energy uses (such as air conditioning and heating) and could have deeper impacts on lifestyles and the economic and social organisation – impacts that must be anticipated in RTE's forward-looking studies.
- High-intensity weather events could lead to common-mode failures (for example, the combination of widespread heatwaves and droughts could simultaneously cause multiple wildfires requiring the shutdown of infrastructures, cooling issues at power plants, and equipment failures).

In this context, RTE has been involved in the work related to the Reference Warming Trajectory for Climate Change Adaptation (TRACC), which establishes a reference scenario of approximately +4°C on average across mainland France. The resulting National Climate Change Adaptation Plan (PNACC3), for which RTE must prepare, includes a specific component on electrical networks. It prescribes adaptation measures to rising temperatures and flood risks as previously mentioned, as well as an updated assessment of the impact of climate change on the electrical system.

France's 2025 network development plan (SDDR) includes a "renewal/adaptation to climate change" component, which will serve as the adaptation plan for the transmission grid infrastructure (RPT) in line with the TRACC.

Improving knowledge of climate change and developing modelling and quantification methods for its consequences represent a major challenge, given the investment trajectory for renewal and climate change adaptation estimated in France's network development plan (SDDR) at €20 billion by 2040.

The 2025-2028 R&D Plan aims to address this "C1" objective through work in two areas:

Understanding the manifestations of climate change

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Maintain RTE's representations of climate change at the state of the art, by incorporating scientific advances and the current state of knowledge (including insights from daily observed climate realities), with deeper investigation into soil temperature phenomena, flooding, and compound events.	Scientific monitoring–analytical impact studies–expert support for relevant R&D activities in prototyping and experimentation.	"Climate, Supply-Demand Balance and Long-Term Network" Programme/"Climate, Weather and Impacts on the Power System" Roadmap

Modelling and quantification of effects on transfer capacities and integration into asset management systems

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Model the effects of global warming on the heating temperatures of equipment (overhead lines, underground cables, transformers) in order to subsequently quantify the impacts on the permissible transfer capacities of network infrastructure, considering the risks of proximity or premature wear. ▸ Characterise and quantify the evolution of fire risk and assess the needs for updating policies and proximity management tools.	Achievement of TRLs 3, 4 and 5 for modelling related to underground conductors, substation equipment, tower foundations and fire risk characterisation.	"Asset Management" Programme/Roadmap: Modelling, "Assessing and Predicting Asset Behaviour"
▸ •Develop methods to identify technical sizing vulnerabilities of network equipment and installations in the face of climate change, and support innovation activities promoting the emergence of adapted new technologies. ▸ •Enhance asset management support systems with models of climate impacts on premature equipment wear and the organisation of maintenance works; studies on consequence valuation, robust sizing, and strategy comparison in light of climate projections for 2030–2050 and beyond.	Achievement of TRLs 3, 4 and 5 for a minimum viable tool to compare strategies based on climate projections for 2030-2050.	"Asset Management" Programme/Roadmap: Modelling, "Assessing and Predicting Asset Performance"

C2. Manage industrial risks and ensure RTE's social responsibility through eco-design, circularity and the preservation of the environment and biodiversity

RTE's industrial transformation project could be jeopardised by the risk of increased global competition for access to the materials and technologies necessary to develop future energy systems. Indeed, recent signals suggest that globalised supply chains may experience recurring disruptions due to the combined effects of massive demand growth (to meet the global needs for renewing aging infrastructure and developing new decarbonised energy sectors), critical raw material shortages[10] and geopolitical tensions.

There is also an already ongoing trend of strengthening regulatory requirements related to eco-design, aimed at compelling economic actors to take into account environmental and biodiversity protection issues, as well as resource consumption sufficiency[11]. This growing body of regulations standards will have the effect of penalising less sustainable industrial practices, relying in particular on standardised non-financial reporting[12] and incentives to steer financing towards activities classified as "sustainable."

In this context, knowledge of the material and technology requirements underlying the scenarios for the development and renewal of the electrical system (and their respective criticalities), as well as understanding the impacts of grid management activities on the environment, ecosystems and biodiversity, are essential pieces of information for managing the exposed risks. Moreover, the emergence of industrial models guided by eco-design criteria and based on increased circularity, recyclability and reparability could help mitigate the effects of supply tensions, facilitate compliance with regulatory requirements and enhance local industrial attractiveness by valorising recyclable material reserves.

Managing these risks will first require having methods and tools to anticipate points of vulnerability. To achieve this, it will be necessary to integrate multiple areas of knowledge:

1. The quantification of the main impacts of transmission grid management activities on the environment, biodiversity, ecosystems and social dimensions.

2. A consolidated representation of the material and technology needs arising from the forecasted trajectories of development, adaptation and renewal of RTE infrastructures, as well as third-party needs related to generation assets, storage and consumption uses (network investments must indeed be aligned with the development of network customer usages),

3. An assessment of the risks of supply-demand tensions on a global scale, taking into account stocks and processing capacities, competition for demand with other economic sectors or geographic regions, the emergence of substitute solutions where applicable and geopolitical factors influencing major global trade balances.

4. An assessment of the evolving environmental regulatory constraints[13], notably those rapidly developing related to the protection and restoration of biodiversity and ecosystems, which may either restrict RTE's activities or, conversely, provide opportunities by promoting best practices.

10. Confer, par exemple: Christophe Poinssot, BRGM, Chief Scientific Officer, Présentation au World Materials Forum 16-18 juin 2022
11. Plan industriel du pacte vert (Green Deal), Règlement " Taxonomie ", Net Zero Industry Act, Critical Raw Materials Act, Règlement Ecoconception (ESPR)…
12. *Cf.* Directive européenne CSRD (Corporate Sustainability Reporting Directive) Découlant par exemple du Pacte vert européen (Green Deal European)
13. Arising, for example, from the European Green Deal

The consolidation of criteria related to the various individual components into a systemic representation will be essential to ensure that decisions made are consistent with the targeted objectives and that efforts are focused on the highest value-added actions.

Secondly, after identifying the most critical vulnerabilities, it will be necessary to validate the technical feasibility and success conditions of alternative solutions based on eco-design criteria as well as circularity, recyclability and reparability, and then to identify the economic models conducive to the emergence of new supply chains to meet RTE's needs.

By way of illustration, the emergence of industrial alternatives to SF6 gas for insulating electrical substation equipment, as well as managing supply tensions for copper, constitute two key topics for the R&D roadmap.

The 2025-2028 R&D Plan aims to address this "C2" objective through work in four areas:

Control of greenhouse gas (GHG) emissions related to switching and insulation systems

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Identify switching or insulation technologies without SF6 for gas substations that comply with European regulations on fluorinated greenhouse gases and test them to establish proof of concept and pre-industrial demonstrations (evaluating functional performance and organisational impacts).	Testing of a 420 kV SF6-free circuit breaker and a 550 kV DC GIS with SF6-free gas switching, designed to be compact for offshore substations (achievement of TRLs 6 and 7).	"Asset Management" Programme/"Model, Assess, Predict the Behaviour of Assets" Roadmap

Notes: These works benefit from collaborative opportunities and institutional funding within the framework of the Horizon Europe MISSION project.

Environmental quantification and analysis

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Develop scientific methods to identify and quantify the main impacts of transmission grid management activities on the environment, biodiversity, ecosystems and social dimensions, and explore possible adaptations to contribute to their protection and restoration.	Concept validation followed by demonstration of simplified biodiversity inventory protocols related to terrestrial infrastructures (achievement of TRLs 4, 5, 6). Exploratory analysis of adaptations conducive to the protection and restoration of the environment, biodiversity and ecosystems (achievement of TRLs 2, 3, 4).	Programme "Environment, Society, and Foresight"/ Roadmap "Energy, Grid, and Biodiversity" Programme "Environment, Society, and Foresight"/ Roadmap "Eco-design, Environmental and Resilience Analyses"
▸ Identify eco-design models for infrastructure solutions (i.e., infrastructure systems as opposed to individual equipment) and evaluate the gains in durability and resilience. ▸ Identify and compare different models of circularity organisation, notably recycling supply chains, in order to analyse their strengths and weaknesses with regard to RTE's needs and regulatory and industrial constraints.	Proof of concept followed by experimentation of eco-design applied to two pilot infrastructure solutions. Support for the experimentation of "proof-of-concept" supply chains and analysis of organisational models.	"Environment, Society and Foresight" Programme/ "Eco-design, Environmental Analyses and Resilience" Roadmap

Regulation, Green Deal, Environmental Standards

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Conduct technical and regulatory monitoring of network components to anticipate usage restrictions (other than SF_6).	Anticipate and influence regulatory requirements related to transmission network equipment to reduce the risks of non-compliant or financially detrimental industrial choices.	"PRISME: Partnerships, Valorisation, Transformation and Cross-Programme Strategies" Programme/ "Standardisation" Roadmap

Quantification of supply challenges		
Consistency	**Targeted achievements under TURPE 7**	**"Programmes"/ "Roadmaps" contributing to the ambition**
▸ Establish a forward-looking vision of the material balances required for future energy systems (network, generation, electricity conversion assets, etc.) and compare these balances with global economic flow maps (needs, resources, capacities, geopolitical risks) in order to highlight cost drivers and main supply risks for RTE infrastructures.	Methodological design followed by execution of pilot studies.	"Environment, Society and Foresight" Programme/"Future Energy System" Roadmap "Environment, Society and Foresight" Programme/"Eco-design, Environmental Analyses and Resilience" Roadmap

C3. Anticipate risks and opportunities through prospective studies and resilience to high uncertainties, in a context of increased instability

As part of missions set out in the Energy Code (such as the Generation Multiannual adequacy report) or in response to requests from the French government (such as "*Energy Pathways to 2050*"), RTE periodically conducts forward-looking studies on the power system. These studies, like the *Energy Pathways to 2050*, serve as essential references for national energy policy. To ensure the plausibility and consistency of the scenarios analysed, they rely on models derived from scientific research.

The dimensions explored by these studies – and consequently the range of models employed – must evolve in step with changes in the geopolitical, economic, social and environmental context, in order to shed light on emerging aspects of the public debate. For example, the *Energy Pathways to 2050* study implemented several innovations stemming from R&D work, such as modelling of climate change, energy sufficiency scenarios, gas-electricity system coupling and material footprint analysis. Today, the convergence of accelerated decarbonisation and reindustrialisation goals, along with increasing macroeconomic, geopolitical and environmental tensions, raises new modelling challenges. These include cross-sector energy optimisation, access to materials and technologies, potential for energy sufficiency, climate adaptations and the dynamics of European reindustrialisation.

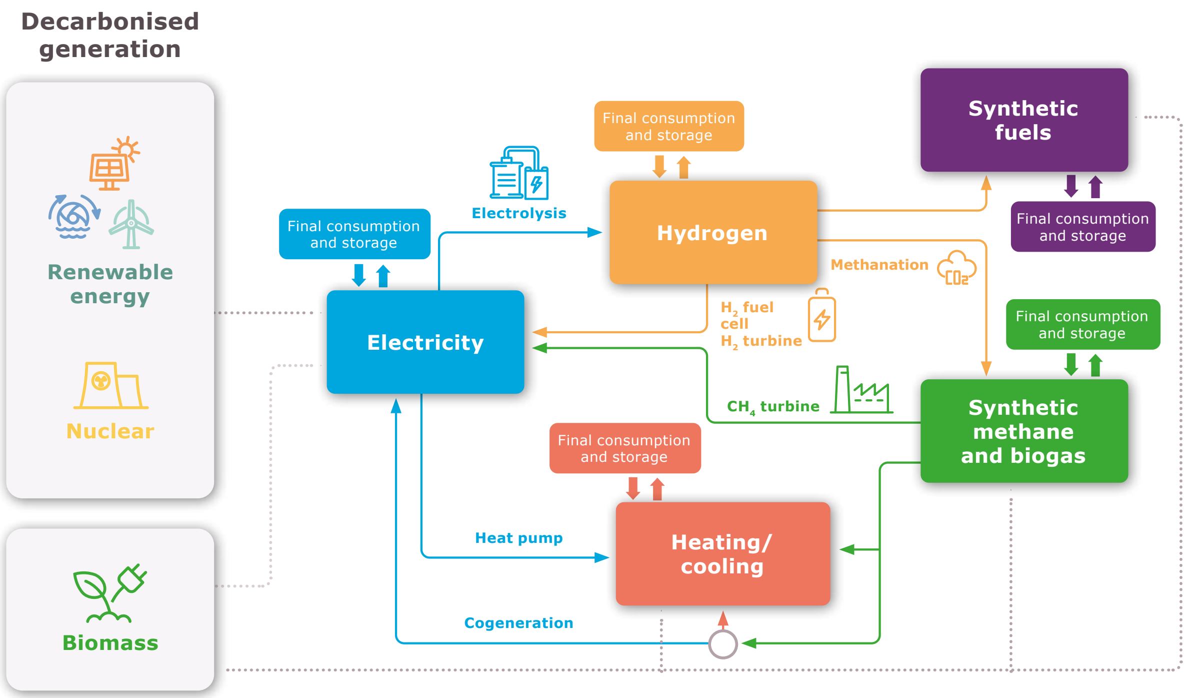
Moreover, these prospective analysis tools also play a key role in the development and critical analysis of asset management and network adaptation pathways. They provide input data for techno-economic studies, help assess the consistency between future investment trajectories and a forward-looking vision of the evolution of the power system and thereby enable robust system sizing by accounting for a range of future scenarios.

Moreover, "out-of-model" risks are materialising. For example, temperatures reached 39°C in Brest during the summer of 2022 – a figure that does not appear in any of the climate scenarios for 2050 provided by Météo-France. Following the 2021 floods, the distribution system operator E.ON decided to relocate its substations beyond the 100-year flood risk zone[14]. Supply chains have been disrupted (due to COVID-19, the war in Ukraine) beyond what was anticipated by markets or procurement planning.

These out-of-model risks are driven by persistent disruption factors: warnings are multiplying about forecasted tensions on copper supplies and, more broadly, on numerous critical resources for energy systems[15]; IPCC impact projections conclude that over three billion people live in contexts highly vulnerable to climate change[16]; vital ecosystem services are threatened by the ongoing collapse of biodiversity[17]; and multiple climate tipping points could be crossed between +1.5°C and +2.0°C[18]. The UN has even pointed to the risk of systemic collapse[19]. In this context of heightened instability, it appears timely and necessary to sustain strong efforts in economic, societal and technological intelligence, as well as in the exploration of possible futures.

14. E.ON presentation at Online Conference: Adaptation & Resilience - Ensuring the energy transition is built on resilient infrastructure, on the 14th of March 2023, jointly hosted by RGI and the European Network of Transmission System Operators for Electricity (ENTSO-E).
15. BRGM studies have highlighted numerous critical elements, and NEXANS has stated that "a copper shortage is inevitable"
16. https://www.ipcc.ch/report/ar6/wg2/resources/spm-headline-statements/
17. https://www.nature.com/articles/nature10548
18. https://www.science.org/doi/10.1126/science.abn7950
19. https://www.undrr.org/gar/gar2022-our-world-risk-gar

FIGURE Main interactions between electricity and other energy carriers



The 2025-2028 R&D Plan aims to meet this "C3" objective through work in two areas:

Methods and tools for prospective and adequacy studies

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Design and then develop a new generation of methods and tools for prospective studies of energy systems and for assessing the adequacy between infrastructures and usages, with appropriate detail ranging from annual energy balances to hourly granularity. These tools should notably be capable of modelling new uses and technologies, accounting for couplings between energy carriers, and producing multi-criteria/multi-capital performance indicators.	Achievement of TRLs 5, 6 and 7.	"Climate, Supply-Demand Balance and Long-Term Grid" Programme/ "Long-Term S&D Modelling" Roadmap "Short-Term Forecasts and Short-Term Supply-Demand Balance" Programme/ "Short-Term S&D" Roadmap "Environment, Society and Foresight" Programme/ "Future Energy System" Roadmap

Economic, social and technological intelligence and exploration of possible futures

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Conduct technological monitoring of energy system components in order to understand their technical, economic and environmental characteristics. ▸ Understand the physical and geopolitical factors related to resources and supply chains necessary for energy systems in order to take them into account in prospective studies (price pressures, delays, shortages). ▸ Explore possible futures of energy systems (environmental, economic and societal contexts; energy uses; production technologies; coupling between energy carriers; cost fundamentals; multi-capital indicators) in order to identify new dimensions that could gain importance in the future (for example, seasonal heat storage), understand their consequences both for RTE's missions and for the overall system operation, and anticipate the required transformations.	Provide well-supported insights on key economic, societal, geopolitical and technological dimensions that could guide future energy foresight studies, similar to the dimensions explored in TURPE 6 that contributed to the Energy Futures Pathways to 2050 (multi-energy coupling, sufficiency).	"Environment, Society and Foresight" Programme/ Roadmap "Future Energy System" "Environment, Society and Foresight" Programme/ "Energy, Grid and Society" Roadmap

2.5 **A cross-cutting objective of collaboration and co-construction** in support of the aforementioned goals

D1. Accelerate and amplify the impact of projects through academic and industrial collaborations, open source, standardisation and the development of shared resources.

The R&D ambitions described above can only be achieved through increased cooperation with a broad network of partners and by integrating scientific innovations from diverse fields. Given the variety of activities to be undertaken, as well as the complexities, novelties and uncertainties involved in each, it will be essential to pool resources with other stakeholders, save time by reusing and sharing results, bring together diverse expertise that RTE cannot assemble alone, rely on cutting-edge scientific developments from both academic and applied research, and promote standardisation and intrinsic interoperability to benefit from economies of scale and facilitate the integration of solutions within the grid and beyond the company's boundaries.

Moreover, this strengthening of collaborations must be promoted not only externally to the company but also internally. In this regard, various best practices derived from open collaboration models can be leveraged to increase productivity by building shared resources (technological, scientific, software, intellectual) across applications, as well as through enhanced interactions between R&D and other stakeholder entities.

National

European

International

Young shoots

Large companies

The 2025-2028 R&D Plan aims to address this “D1” objective through work in four areas:

Scientific collaborations

Consistency	Targeted achievements under TURPE 7	“Programmes”/ “Roadmaps” contributing to the ambition
▸ Explore, based on scientific collaborations, then adapt and validate on RTE’s large-scale use cases, new algorithmic solutions for numerical simulation, robust optimisation, and, more generally, decision support, notably leveraging hybrid techniques combining physical modelling and machine learning to reduce algorithmic complexity and achieve practical performance.	Transfer of multiple algorithmic solutions into prototype or real-scale demonstration applications.	“PRISME Programme: Partnerships, Valorisation, Transformation and Trans-Programme Strategies”/Roadmap: “Trans-Programme Strategy for Decision Support Tools”

Setting up partnerships and seeking funding

Consistency	Targeted achievements under TURPE 7	“Programmes”/ “Roadmaps” contributing to the ambition
▸ Identify partnership opportunities for specific projects and manage their setup (partner search, negotiation of terms, contracting). ▸ Identify opportunities to participate in consortia benefiting from institutional funding (Horizon Europe, France 2030, etc.), contribute to the preparation of application dossiers, and, if applicable, to the setup and administrative follow-up of projects. ▸ Contribute to the emergence and execution of collaborative R&D activities within the CRESYM[20] structure, in line with RTE’s needs, and integrate the results into internal work.	Doubling the volume of collaborations aimed at co-constructing shared resources to support the aforementioned R&D objectives.	«PRISME: Partnerships, Valorisation, Transformation and Cross-Programme Strategies” Programme/ “Partnerships and Valorisation” Roadmap

20. https://cresym.eu/

Standardisation and pre-standardisation

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Structure and coordinate contributions to the development of standards, notably through monitoring, risk and opportunity analysis, drafting proposals and participating in committees and working groups (including, among others, leading the «WS9: Green Electricity System» of the High-Level Forum on European Standardisation), with a focus on standards related to grid stability requirements, those arising from the Ecodesign Regulation (ESPR) and those concerning the interoperability of high-voltage direct current (HVDC) technologies.	Orientation of standardisation efforts in the mentioned areas in line with RTE's industrial transformation needs, with a focus on achieving the best cost-efficiency.	"PRISME Programme: Partnerships, Valorisation, Transformation and Cross-Programme Strategies / Roadmap: Standardisation"

Open source

Consistency	Targeted achievements under TURPE 7	"Programmes"/ "Roadmaps" contributing to the ambition
▸ Continued involvement in the governance and development of the LF Energy foundation[21] to increase the scale, industrial robustness and innovation dynamics of the projects hosted there through the adoption of open source best practices and community development. ▸ Building on the successes achieved, work towards the emergence of new open source collaborations to support R&D activities during the TURPE 7 period.	Doubling the volume of open source collaborations aimed at the co-construction of shared resources to support the aforementioned R&D objectives.	"PRISME Programme: Partnerships, Valorisation, Transformation and Cross-Programme Strategies/Roadmap: Open Source"

21. https://lfenergy.org/

Implemented R&D models

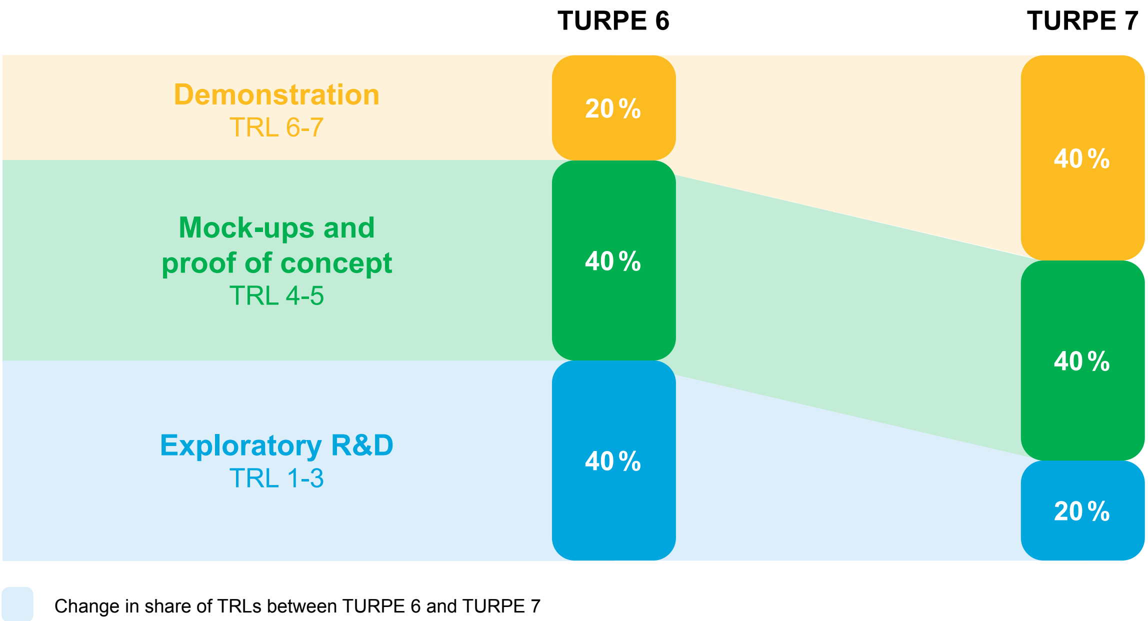
3

3.1 Growth and Acceleration

The R&D plan for the TURPE 7 period, whose objectives outlined above are guided by corporate, sectoral and societal priorities, represents a significant increase in ambition compared to the TURPE 6 period. This evolution responds, on one hand, to a multiplication and strengthening of various industrial challenges, as described in the previous chapter ("Objectives of the 2025-2028 R&D Plan"), which it seems appropriate to address through R&D actions, and on the other hand, to the necessity of acceleration so that R&D results are available ahead of the transformations RTE will need to undertake in order to have an industrial impact.

The need for acceleration is particularly reflected in the distribution of the R&D effort by targeted maturity level for the TURPE 7 period:

FIGURE Change in target allocation of R&D efforts by maturity level



3.2 Create and leverage more collaboration opportunities to pool resources and accelerate the pace of innovation

On 30 January 2024, RTE organised an online conference titled "Empowering an accelerated energy transition–The next R&D ambition" to present the R&D ecosystem partners with an initial vision of the R&D challenges to be addressed during the 2025-2028 period. This event brought together more than 500 participants from around the world, representing over 200 entities, including European grid operators, international industrial companies, service providers, startups, academic and research institutions, and public administrations. A survey conducted during the event, with 184 respondents, revealed that over 90% of respondents consider R&D essential to the energy transition; more than 80% believe that the share of R&D in the electric grid value chain must significantly increase compared to the previous decade; and a large majority think that the activity programme planned by RTE appears qualitatively relevant, or even insufficiently ambitious. Furthermore, nearly two-thirds of respondents believe that RTE is a leading player in collaborative R&D, almost three-quarters consider that RTE should further promote open collaboration models and more than 80% see potential opportunities for co-investment with RTE in some of the presented R&D projects.

The multiple R&D partnerships initiated during the TURPE 6 period and the investment in the development of the two flagship vehicles, LF Energy[22] and Cresym[23], reflect the conviction that strengthening collaborations will be an essential factor in achieving R&D objectives. For the TURPE 7 period, this strengthening objective is driven by the cross-cutting activities previously described in the "D1. Accelerate and amplify the impact of projects through academic and industrial collaborations, open source, standardisation and the building of shared resources" section.

LF ENERGY STRATEGIC MEMBER

CRESYM

22. www.lfenergy.org
23. https://cresym.eu/

3.3 **Strengthen R&D collaborations** between Transmission and Distribution

A particularly important area of collaboration during the TURPE 7 period will be between RTE and the French Distribution System Operators (DSOs). These collaborations will be essential for several reasons:

- For the coordination of investment trajectories: in a context of rapidly growing needs for infrastructure adaptation and renewal, the joint development of common elements for investment study methods and tools (techno-economic modelling, risk analysis and robust optimisation) will enable a better representation of interactions between the two networks, facilitate information sharing and provide deeper mutual understanding – ultimately contributing to more coherent decision-making.
- For the performance of operational network management: by exploring opportunities to pool resources and coordinate levers for managing power flows and voltage levels.
- To create favourable conditions for efficient long-term supply-demand balancing through structural load modulation and usage flexibility: by identifying shared interoperability mechanisms and components that network operators could promote to support the development of usage control systems for consumers and the emergence of appropriate tariff offers from suppliers, and by conducting field experiments (demonstrators) to validate the technical, economic, regulatory and contractual success conditions.
- More generally, to pool resources and expertise dedicated to shared research and development challenges, for example in the field of asset management.

An important first step was taken during the TURPE 6 period with the signing, on 15 December 2022, of an R&D partnership agreement between RTE and GÉRÉDIS Deux-Sèvres, the electricity distribution network operator under concession from the Syndicat Intercommunal d'Énergie des Deux-Sèvres (SIEDS). This agreement identifies six exploratory areas (or "action sheets") in which the two companies plan to collaborate on R&D:

1) network modelling and associated tools,

2) flexibility levers and interactions between networks,

3) joint network development integrating available flexibilities,

4) predictive model of vegetation growth,

5) automatic fault detection & LIDAR data analysis and classification,

6) maintenance/renewal arbitration, relationship between detected equipment faults and incidents.

Joint work has been underway since 2022, with notable progress particularly in areas 1, 4 and 5. The resources allocated have remained modest so far, in line with the funding provided in the tariff trajectories (TURPE 6/ FPE 2022-2025). RTE and Gérédis now recognise a mutual interest in increasing the ambition of the collaboration during the TURPE 7 period.

Subject to the budgetary resources allocated in their respective R&D roadmaps, RTE and Gérédis intend to pursue the following ambitions for the 2025-2028 period:

1) With a coordination objective aimed at better optimising investment trajectories:

- Continuation and strengthening of work related to the development of network study methods and tools, as well as the creation of shared data sets, in continuity with the “action sheet No. 1” mentioned above;

- Exploration of methods enabling the joint optimisation of maintenance, renewal, and asset development actions, with particular focus on modelling the impact on service delivery and quantifying residual industrial and operational risks;

- Definition and execution of a pilot study to demonstrate the value of seeking coherence for assets at the interface (substation).

2) Regarding the objective of coordinating levers for the operational management of the networks:

- Continuation and strengthening of the work on the action sheet “flexibility levers and interactions between networks,” initially focusing on the issue of voltage management. The first step would be to demonstrate, through a techno-economic study, the operational gains of coordinated dynamic management of reactive power setpoints using various levers (generation sites, STATCOM equipment in substations), followed by validation of the results and feasibility through a demonstration in a test environment or even operational setting.

3) Regarding facilitating structural modulation and flexibility of usage:

- Opportunity study, definition of specifications, and, if applicable, implementation of a demonstrator at the scale of the Deux-Sèvres territory, with the objectives of identifying shared interoperability devices and components that network operators could promote to facilitate the emergence of usage management systems for consumers and the development of appropriate tariff offers by suppliers, as well as validating the technical, economic, regulatory and contractual conditions for success.

4) Regarding the objective of pooling resources and expertise in the field of asset management:

- Continuation and strengthening of work related to predictive modelling of vegetation growth, in line with the above-mentioned “action sheet No. 4.”

- Continuation and strengthening of work related to automatic fault detection and the analysis and classification of LIDAR data, in line with the above-mentioned “action sheet No. 5.”

These activities, along with the corresponding budgets for RTE, are included in the R&D efforts described with respect to objectives A1, A2, B2 and B3.

The implementation of the demonstrators mentioned in points 2 and 3 above will likely require additional funding beyond the incentive regulation for R&D under the TURPE framework. The corresponding financing plans will be defined as part of the preliminary studies mentioned.

Finally, RTE and Gérédis aim to disseminate the results of their collaboration as openly as possible, preferably through open-source channels, with the objective of enabling reuse and even the emergence of collaborations beyond this bilateral framework.

Programmes and Roadmaps

4

4.1 Short-Term Supply-Demand Forecasting and Balancing Programme (PICTEO)

The Short-Term Supply-Demand Forecasting and Balancing Programme aims to develop a set of tools and methods to support power system operators (and operational processes) in anticipating injections, withdrawals and supply-demand balancing on the grid, across time horizons ranging from seven days ahead to real time.

This programme is composed of two roadmaps:
- Short-Term Forecasting
- Short-Term Supply-Demand Balancing

Roadmap: "Short-Term Forecasting"

The objective of the roadmap is to design, prototype, and test innovative methods for forecasting injections and withdrawals, with the aim of improving performance through hybridisation techniques combining physical models and artificial intelligence, diversifying data sources (multi-model and multi-provider forecasts) to reduce and better characterise associated uncertainties, automating the entire pipeline from model training to execution, and integrating exogenous information provided by stakeholders as well as modelling modulation behaviours in response to market signals (and other flexibility behaviours).

Roadmap: "Short-Term Supply-Demand Balancing"

This roadmap aims to study the necessary evolutions in supply-demand balancing processes, in order to account for changes in the uncertainty profiles of generation and consumption, the shortening of operational time windows, market dynamics and actor behaviours, the emergence of new balancing service providers, and the development of European balancing energy exchange platforms. It also aims to prototype and test decision-support tools that enable operators to manage system balancing in an efficient and controlled manner. Finally, it addresses the interactions between operational processes for flow management and supply-demand balancing.

4.2 "Grid Operation and Control" Programme (PILOT)

The Grid Operation and Control Programme aims to develop a set of tools and methods to support power system operators (and operational processes) in managing power flows on the grid and selecting efficient and robust operational trajectories, across time horizons ranging from two days ahead to real time.

This programme consists of two roadmaps:
- Flow Management
- Interactive Smart Cockpit

Roadmap: "Flow Management"

This roadmap aims to design, prototype and test new solutions for network operational security analysis and decision support, based on state-of-the-art scientific techniques (numerical simulation, artificial intelligence, robust optimisation, hybridisation of optimisation methods and machine learning). These solutions will enable modelling of the network's operational complexities, temporal dynamics, uncertainties, and the corrective action capabilities provided by various flexibility levers and will propose to operators the preventive actions necessary for the reliable operation of the network.

Roadmap: "Interactive Smart Cockpit"

This roadmap aims to redesign the human-machine interface and develop intelligent bidirectional assistance systems to help operators make effective and rapid decisions while managing increasing complexity and information overload, especially in dynamic, constrained and even critical operational contexts.

4.3 "Grid Stability Control and Simulation" Programme (MAESTRO)

The Grid Stability Control and Simulation Programme aims to provide the scientific framework, methods and tools enabling RTE to ensure stability control and power quality of the grid in the face of the expansion of decentralised generation, new types of consumption and power-electronics-based conversion interfaces.

This programme consists of two roadmaps:

- Electrotechnical Simulators of System Operation
- Stability of a Rapidly Changing System

Roadmap: "Electrotechnical System Operation Simulators"

This roadmap aims to enhance the Dynaωo software suite, which provides a range of open-source, flexible, scalable, interoperable, transparent and robust simulation tools for conducting a wide spectrum of grid studies, with improved consideration of newly connected technologies. The focus is on developing a module to simulate slow interactions between converters and a dynamic simulator for short-circuit current calculation.

Roadmap: "Stability of a Rapidly Evolving System"

The purpose of this roadmap is to develop the knowledge and methods necessary for RTE to ensure the stability of the power system in the context of ongoing transformations (connection of new types of generation and consumption, either high-power or decentralised, and the expansion of power-electronics interfaced components). The roadmap addresses the needs for i) defining requirements for new grid-connected devices, ii) designing tools to enable enhanced and near real-time monitoring of grid stability, iii) identifying the means necessary for efficient management of these risks and iv) rethinking system operation and protection to ensure its resilience.

4.4 "Voltage, Protection and Stability" Programme (TENPOS)

The Voltage, Protection and Stability Programme aims to study the impacts of the gradual transformation of grid-connected assets (including the expansion of power-electronics interfaced components, new types of generation and consumption – both high-power connected to the transmission grid and decentralised connected to distribution networks) on the maintenance of power system stability and quality. The programme focuses specifically on the behaviour of power-electronics equipment (HVDC stations, inverters), voltage management devices, and protection schemes. It seeks to identify and provide recommendations for the evolution of regulatory and standardisation frameworks for grid connections, as well as internal mechanisms ensuring the secure operation of the system.

The programme is composed of three roadmaps:
- Power Electronics and Direct Current
- Voltage
- Protections

Roadmap: "Power Electronics and Direct Current"

This roadmap aims to study the impact of the gradual increase of power-electronics-based active equipment on grid stability, grid architecture and grid operation. It is composed of three complementary areas of study:
- DC Connection and Direct Current Networks
- Interactions and Interoperability in a Hybrid (AC and DC) System
- New Opportunities Offered by Power Electronics-Based Equipment

Roadmap: "Voltage"

This roadmap aims to develop the knowledge, methods and tools that will enable RTE to ensure efficient voltage management of the power grid across all time horizons, from real time to long-term planning. The work it comprises is structured around four complementary areas:
- Improvement and enhancement of data to enable observation of various phenomena.
- Development of models and algorithms to accurately simulate the voltage behaviour of the grid.
- Design of methods and tools to monitor, control, and support anticipatory voltage management.
- Conducting studies to inform investment decisions and the need for changes in devices, regulatory frameworks or standards related to voltage management.

Roadmap: “Protections”

The design of current protection systems is based on models of grid behaviour under fault conditions that were developed prior to the rise of power-electronics-based converters. This roadmap therefore aims to study the impact of an increasing share of converters on the performance of protection systems during faults affecting the grid, in order to assess the risk of malfunctions and propose technical or regulatory adjustments. To this end, the planned work aims to:

- Identify synthetic indicators that can highlight operating conditions under which current protection systems may fail to function effectively.
- Using these indicators, identify high-risk operating scenarios for the transmission network, both from a geographical and temporal perspective.
- In collaboration with protection system manufacturers, identify solutions to mitigate the risk of malfunctions. Similarly, identify the most favourable grid code evolutions for protection system performance.
- Propose an evolution of the protection plan for the transmission network, with a primary focus on the 63 kV and 90 kV voltage levels, which are the most impacted and interface with the distribution network

4.5 "Asset Management" Programme (GA)

The Asset Management Programme aims to design and develop innovative methods and tools to support RTE's asset management. This programme addresses the need to improve understanding of asset conditions and degradation, notably through modelling and numerical simulation based on physical models and data; to simulate asset management policies, incorporating representations of failure risks and consequences to help determine optimal strategies; and to automate network inspections using new technologies while improving working conditions for field operators

This programme is structured around three roadmaps:

- Network Inspection Automation and Modernisation of Intervention Means (AIRM²I)
- Modelling, Assessing and Predicting Asset Behaviour
- Asset Management Support Systems (SAGA)

Roadmap: "Network Inspection Automation and Intervention Means Modernisation" (AIRM²I)

This roadmap aims to develop innovative solutions to facilitate and automate inspection and intervention activities on the electricity transmission network, leveraging new technologies – particularly through the use of increasingly autonomous platforms (helicopters, drones, robots), sensors, satellite imagery and data processing via Artificial Intelligence.

The R&D work carried out under this roadmap will primarily consist of:

- Experimentation with a data acquisition and processing chain for photographic and LiDAR data using helicopters and then drones, focusing on sensor specifications, algorithmic and AI processing, while maintaining monitoring of advancements in long-range "Beyond Visual Line Of Sight" (BVLOS) drone technology.
- Experimentation with the combination of satellite imagery and AI algorithms for automatic and large-scale event detection or targeted inspections (such as vegetation proximity, third-party construction sites, work inspections, etc.).
- Experimentation with the use of autonomous drones for remote monitoring and inspection of electrical substations, as well as detailed inspection of pylons.
- Ensuring the industrial transfer of experimental results related to robots for inspecting confined or hazardous access areas.
- Continuing the development of a new combination for live-line work.
- Contributing to the development of drone operations for live-line work techniques.

Roadmap: “Modelling, Assessing and Predicting Asset Behaviour”

Optimising asset management for economic efficiency, sustainable development and operational capacity requires more sophisticated methodological approaches than simply replacing assets upon reaching a predefined age limit. Other alternatives must be considered, such as rehabilitation, upgrading or differentiated maintenance levels. Choosing among these options requires estimates of asset damage, based on simulations or observations, taking into account past and future stresses along with the associated uncertainties.

Controlling greenhouse gas emissions is also a major challenge in asset management. To this end, RTE must identify alternatives to SF6 (a gas with excellent electrical insulation properties but a high global warming potential) for gas-insulated switchgear, experiment with the feasibility of gas replacement and prepare the conditions for its deployment.

The R&D work carried out under this roadmap will primarily consist of:

- The completion, industrial transfer and deepening of work undertaken in the field of overhead line connections (PALLAS project), including multi-physical (thermal, mechanical fatigue, fretting, corrosion) and multi-scale modelling – from the span level to strand-to-strand contacts – allow for the assessment of conductor damage based on loading histories, as well as the validation of aging models associated with non-destructive testing, and the development of digital twins of overhead line systems (from conductors to towers and their foundations).
- The continuation of research work related to non-destructive testing, corrosion of overhead lines (conductors, towers, corrosion under paint), and foundation aging,
- The extension of these methodological approaches to underground and submarine cables (data collection, mechanical and thermal modelling, characterisation of insulating aging, modelling and simulation of dynamic cable behaviour), to characterise, model and simulate the fatigue and aging conditions of these assets, within a context of resilience to climate change,
- The advancement of thermal modelling of conductors (overhead and underground), applications in ampacity calculation codes (Dynamic Line Rating applications), and the consideration of climate change, with a particular focus on the challenges related to the propagation of uncertainties in data and models on the results.
- The study of the possibilities for retro filling the passive compartments of gas-insulated substations (GIS) with a gas alternative to SF6.
- The experimentation and validation of monitoring and surveillance conditions for power transformer bushings, which are particularly vulnerable and whose failure consequences are significant.
- The testing of new equipment without SF6 (420 kV SF6 circuit breaker and compact 550 kV DC GIS for offshore substations).

Roadmap: "Asset Management Support Systems" (SAGA)

This roadmap aims to develop innovative methods and tools, based on reliability theory and consequence valuation, to assist in optimising investment decisions according to value criteria and risk management for RTE and the community. This optimisation must encompass the development, renewal, and maintenance of infrastructure within a context constrained by resources, implementation capacity and the ability to take the network offline.

The R&D work carried out under this roadmap will mainly consist of:

- Continued development and expansion, by creating models tailored to RTE's needs, a solid foundation of relevant scientific knowledge (reliability theory, renewal theory, risk science, socio-economic optimisation) and its dissemination through documentation and training materials.
- Collaboration in defining a shared "Risk Informed Decision Making" methodological framework within ENTSO-E and CIGRE, as well as within the company.
- Participation in the integration of these methods into standardisation work (IEC, CENELEC, AFNOR), particularly in the IEC 123 standard.
- Continued development of the Relife Open Source computation library, which implements optimisation methods in asset management, and building a user community around this tool and reliability calculation models.
- Continued targeted use, incremental transfer to users and functional enhancement of the holistic asset management policy simulator "Mona."
- Continued demonstration and functional improvement of the "Scoop" prototype to assist with the annual scheduling of outages and preparing its integration into regional operational planning activities.
- Analysing and identifying the required changes to preventive maintenance policies (current OMF policy – "Optimisation of Maintenance by Reliability") to take into account the capabilities and knowledge provided by the aforementioned methods and tools, feedback from the current policy and technological developments of the assets, as well as developing the methods and algorithms necessary for the evolution of these policies.
- Designing and prototyping methods for optimising engineering project portfolios (connection and reinforcement, renewal, rehabilitation) based on the definition of value and consequence frameworks.

4.6 "Future Cyber-Physical and Eco-Designed Network Infrastructures" (FCEIR) Programme

The "Future Cyber-Physical and Eco-Designed Network Infrastructures" programme aims to design and develop new innovative hardware and software infrastructure solutions to enable the efficient and accelerated adaptation of the grid to future needs.

This programme consists of three roadmaps:
- Cyber-Physical System Architecture
- Substation Automation Virtualisation
- Maritime

Roadmap: "Cyber-Physical System Architecture"

The network control architecture must evolve to integrate more distributed automation within the system, with the dual purpose of increasing the network's capacity to accommodate new uses and leveraging advanced automation to manage a portion of operational uncertainties, particularly over very short time horizons.

The R&D work carried out under this roadmap covers three areas:
- The design, development and demonstration of core calculation algorithms for automation in the operational management of transit or voltage constraints on the grid. These algorithms are notably integrated into the NAZA (New Adaptive Zone Automata) for managing high-voltage congestion at the HTB1 level (90–63 kV). Algorithms for use cases not covered by NAZA are also under study.
- The development of platforms to simulate the operation of automation systems within their environment, which intertwines the electrical system and digital infrastructures (software, communication networks). These co-simulation platforms will allow to understand the functioning of these complex systems for purposes such as pre-operational qualification, maintenance, operational analysis or resilience studies in the face of operational incidents.
- The study of more decentralised control architectures for the cyber-physical system than those traditionally used, focusing notably on resilience properties, cybersecurity and operational modes.

Roadmap: "Substation Automation Virtualisation"

Similar to the technological shifts undertaken in the telecommunications and automotive sectors, virtualisation technologies for real-time protection, automation and control systems are set to be applied to electrical networks. This involves replacing hardware equipment with software applications running on a virtualisation software infrastructure and on common hardware. Virtualisation – a true technological breakthrough – is expected to enable a significant reduction in the equipment to be installed, simplify engineering and reduce operating and maintenance costs through remote diagnostics, remote administration and remote maintenance.

The R&D work carried out under this roadmap will consist of:

- Demonstrating, first in the laboratory and then under real operating conditions, a virtualised substation control system solution, involving multiple vendors, running on an open-source virtualisation infrastructure[24], including protections against insulation faults.
- Characterising the changes required in business processes to support this new solution and assess the technical and economic benefits over the full lifecycle.
- Contributing to the technical specifications for a future industrial deployment of this solution.

If these steps prove successful, industrial implementation projects for the virtualised protection systems could be launched as early as the 2029-2032 period.

Roadmap: "Maritime"

The "Maritime" roadmap is primarily aimed at exploring and optimising RTE's design choices for the connection of deep offshore wind power. To this end, the work will be mainly focused on a demonstration project, a study project and an upstream research project.

- The Rhodé project, which aims to verify the feasibility of floating HVDC 2GW connections, with a specific focus on floaters, dynamic cables, embedded power electronics and onboard extra high-voltage equipment.
- The study of fixed substations for depths exceeding one hundred metres as an alternative to floating connections
- The exploration of a more disruptive connection concept using high-power alternating current technology with superconducting cables ("Supra Marine").

In addition, the roadmap also includes studies to understand, measure and, where necessary, mitigate the impact of offshore grid infrastructure on marine and coastal biodiversity. This notably includes the study and demonstration of an innovative solution to reduce noise pollution caused by pile driving (or drilling) for the foundations or anchoring systems of offshore platforms.

24. SEAPATH project (https://lfenergy.org/projects/seapath/)

4.7 “Climate, Long-term Supply-Demand Balance and Grid” (CLER) Programme

The “Climate, Long-term Supply-Demand Balance and Grid” programme is designed to develop the knowledge, methods and tools required for long-term techno-economic studies across four key dimensions: climate, the evolution of consumption and usage patterns, supply-demand balance and power system adequacy studies, and grid adaptation and development studies.

This programme is therefore composed of four roadmaps:

- Climate, Weather and Impacts on the Power System
- Decarbonisation, Electrification and Flexibility of Consumption
- Long-Term Supply-Demand Balance Modelling
- Network Evolution

Roadmap: “Climate, Weather and Impacts on the Power System”

The objective of this roadmap is to provide RTE with knowledge, methods, tools and data on the current climate and its future evolution, as well as the resulting impacts on the management of network infrastructures and, more broadly, on the French and European power system.

To this end, it involves maintaining state-of-the-art representations of climate change used by RTE, by integrating scientific advances and the current state of knowledge (including lessons learned from ongoing climatic realities), with deeper understanding of phenomena such as soil temperature, flooding and combined events. It also involves contributing to the development of various functions that translate climatic parameters into impacts on network management.

Roadmap: “Decarbonisation, Electrification and Consumption Flexibilities”

The objective of this roadmap is to develop models and datasets that characterise and scenario long-term evolutions of electricity usage (annual energy consumption, hourly profiles, location and flexibility capacities). This knowledge is primarily used in RTE’s prospective studies and planning activities: the Multiannual Reports, France’s network development plan (SDDR), connection planning, and more.

Roadmap: “Long-Term Supply-Demand Balance Modelling”

The objective of this roadmap is to design, prototype and then develop new methods and tools for prospective studies of energy systems and the adequacy between infrastructure and usage, with hourly granularity. These tools should notably be capable of modelling new uses and technologies, accounting for couplings between energy carriers, and producing multi-criteria performance indicators.

Roadmap: “Grid Evolution”

The objective of this roadmap is to design, prototype, and then develop new methods for multi-scenario techno-economic studies of the transmission network. These methods should enable the assessment of infrastructure evolution needs, the connection capacities for new customers and the planning constraints related to outages for maintenance operations. This will rely on scientifically innovative simulation and optimisation algorithms to automate techno-economic calculations and to represent the complexity of phenomena with the best balance between realism and computational constraints. Among these complexities, particular attention will be given to modelling new uses such as battery storage, as well as accounting for flexibility and automation.

4.8 “Environment, Society and Prospective studies” (PEPS) Programme

The purpose of the “Environment, Society and Prospective studies” programme is to help RTE anticipate and prepare the French electrical grid and system for future contexts, by integrating requirements of sustainability and resilience. This requires developing analytical, foresight and action tools with a comprehensive understanding of the electrical system: technical, economic, social and environmental.

This programme is therefore composed of six roadmaps:

- Network and Biodiversity
- Eco-design, Environmental and Resilience Analyses
- Regenerative Lines
- Energy, Network and Society
- Flexibility and Regulation
- Future Energy System

Roadmap: “Network and Biodiversity”

The ambition of this roadmap is to improve RTE’s ability to understand the interactions between infrastructure and the marine landscape, environments and living organisms through rigorous and verifiable scientific approaches. Furthermore, to develop network solutions that reduce negative impacts and contribute to biodiversity regeneration, new concepts of solutions and practices are being explored. The roadmap is organised into three biodiversity domains:

- In marine biodiversity, several topics are addressed: the effect of electromagnetic fields on marine biodiversity during the operational phase, the improvement of environmental impact studies, the understanding of interactions between infrastructures and ecosystems, as well as the characterisation of risks related to pollution.
- In terrestrial biodiversity, the projects focus on characterising the effects of forest trenches and electrical substations on biodiversity, as well as on characterising the environmental services provided by the areas occupied by forest trenches.
- Regarding avifauna, the primary objective is to reduce the risk of bird collisions with electrical infrastructures through a better understanding of the interactions between the infrastructures and birdlife, as well as the testing of innovative solutions.

Roadmap: “Eco-design, Environmental Analyses and Resilience”

In a global context of exceeding planetary boundaries, this roadmap aims to develop methods of analysis, evaluation, design and decision-making that integrate sustainability and resilience requirements. In T7, these methods will be primarily applied and tested in the eco-design of hardware assembly designs or engineering processes for RTE.

Roadmap: “Regenerative Lines”

The concept of “Regenerative Lines” involves integrating nature-based ecological functions into our network projects: regulation of the water cycle, creation of carbon sinks, enhancement of pollinators and beneficial insects, combating heat islands and wildfires, and restoring ecological connectivity. The objective of the R&D work carried out under this roadmap will be to experiment with the integration of such functions, assess the reception by local stakeholders and then study the technical, economic and governance conditions necessary for the concept to be industrialised at scale.

Roadmap: “Energy, Grid and Society”

This roadmap aims to understand the relationships between energy, the grid and society to identify the success factors for energy transition. The work covers three areas:

1. The relationship between society and infrastructure: understanding the mechanisms of opposition and support for infrastructure projects and proposing changes in practices likely to promote acceptance and thus the success of France’s network development plan (SDDR).

2. The social foresight of energy is organised around two main axes:
    - The major trends in energy consumption, addressed through the history of prospective studies and consumption planning, as well as through social norms of consumption.
    - The social conditions for demand reduction, following the 2023 Multiannual adequacy report study, which shows that energy conservation is an essential pillar. This is approached through the forms and experiences of energy conservation, the prioritisation of uses, the relationship to demand under constrained electrical conditions and energy justice as a condition for change.

3. Planning and territorialisation, focusing in particular on offshore developments, the dynamics of self-consumption, the evolving role of energy unions and the effects of regional COPs[25] on territorial planning and network projects.

Roadmap: “Flexibility and Regulation”

The ambition of this roadmap is to study regulatory and techno-economic regulatory mechanisms and their effects on long-term supply-demand balance and the sustainability of the electricity transmission network. The work covers four areas:

- Development of flexibility: identify the conditions for the development and activation of flexibility, and study, in collaboration with the external ecosystem, governance and economic models to ensure a “harmonious” management of the “duck curve.”
- Management of stress situations and structural mismatches between supply and demand: understand and anticipate stress situations related to supply-demand adequacy, including possible load shedding, at the French and European levels and analyse the effects of various potential regulatory mechanisms in order to derive recommendations.

25. https://www.ecologie.gouv.fr/politiques-publiques/cop-regionales

- Investment profitability: develop an operational method to assess the profitability of investments, whether in production assets or network infrastructure, under varied assumptions regarding the energy mix, consumption, and regulatory framework, with the aim of identifying scenarios in prospective studies that would inherently be economically unsustainable or unstable, unless new subsidy mechanisms are considered.
- Regulation and sustainable finance: anticipate European regulatory developments (e.g., CSRD) and propose changes to RTE's financing mechanisms (tariffs and others).

Roadmap: "Future Energy System"

The objective of this roadmap is to build a prospective vision of the French electrical system within a comprehensive and coherent economic analysis framework. To achieve this, the roadmap is structured around four interconnected pillars:

- Quantitative scenario development: demographics, lifestyles, technological choices, reindustrialisation, energy and environmental policies.
- Structural evolution of the economy and its energy and environmental footprint, in trajectory, through monetary and physical "input-output" modelling.
- Energy needs by carrier and operation of the coupled European energy system: electricity, gas, hydrogen, heat and implications for sizing.
- Fundamentals of costs and industrial sectors: requirements for materials, industrial capacities and supply chains.

The roadmap also includes a technology watch activity that feeds into the previously mentioned areas of study.

4.9 Programme: "Partnerships, Valorisation, Transformation and Cross-Programme Strategies" (PRISME)

The "Partnerships, Valorisation, Transformation and Cross-Programme Strategies" programme aims to develop the scientific, technological and commercial partnerships necessary for the efficient completion of R&D projects, to foster connections between academic research and RTE's industrial needs in order to bring forth new solutions, to seek opportunities for additional funding, and to promote a streamlined vision and the creation of common resources to coordinate and pool R&D efforts. It is composed of four roadmaps:

- Partnerships and Valorisation
- Standardisation
- Open Source
- Strategies for Decision Support Tools

Roadmap: "Partnerships and Valorisation"

This roadmap aims to identify and develop partnership opportunities and to support their structuring and monitoring. In doing so, R&D activities can be carried out efficiently by fully leveraging collaboration mechanisms, complementary institutional funding and coordination with the external ecosystem. More specifically, this will involve:

- Identifying partnership opportunities for specific projects, particularly by seeking leverage effects (co-construction, co-financing).
- Identifying opportunities to participate in consortia benefiting from institutional funding (Horizon Europe, France 2030, etc.), contributing to the preparation of application files, and supporting the administrative setup and follow-up of projects.
- Harmonising and improving contractual and partnership practices (governance, intellectual property, etc.).
- Promoting R&D activities aligned with RTE's needs within appropriate scientific, institutional and industrial bodies.
- Disseminating and showcasing RTE's R&D results and, conversely, capturing developments from the external ecosystem to support better sector-wide coordination beyond the boundaries of the company.

Roadmap: "Standardisation"

This roadmap aims to identify the main standardisation challenges relevant to the fulfilment of RTE's missions, to coordinate participation in standardisation work in order to ensure that RTE's needs are taken into account, and to anticipate regulatory and normative requirements to manage associated risks and facilitate compliance. More specifically, this will involve:

- Strengthening RTE's representation within major standardisation bodies.
- Conducting technical and regulatory monitoring and participating in the development of equipment-related standards, in order to anticipate and influence requirements so as to reduce the risks of non-compliant or financially disadvantageous industrial choices, and to lower the total cost of infrastructure (e.g., simplified procurement, standardised specifications, economies of scale, interoperability, optimised operation and maintenance).

- Promoting the implementation of equipment and methodological standards that address the challenges of electricity stability and quality, particularly with regard to grid forming.
- Promoting the implementation of standards enabling the large-scale development of flexibility solutions for grid balancing, particularly FlexReady.

Roadmap: "Open-Source"

This roadmap aims to consolidate, develop and promote the Open Source strategy adopted by RTE[26]. The objectives of the roadmap include:

- Continued contribution to the governance and development of the LF Energy Foundation, in order to strengthen the scale, industrial robustness and innovation momentum of the projects it hosts, through the adoption of Open-Source best practices and the development of communities.
- Building on past successes, working toward the emergence of new Open-Source collaborations to support and optimise R&D activities during the TURPE 7 period.
- Promoting the Open-Source collaboration approach both internally and externally through experience sharing, quantification of benefits and continuous improvement of practices.

Roadmap: "Decision Support Tools Strategy"

This roadmap aims to provide innovative methodological and algorithmic solutions for operational decision-support applications (real-time operations, asset forecasting management, power grid infrastructure development, test laboratories, closed-loop control, etc.). These solutions focus in particular on four key areas (modelling, simulation, control, and optimisation) which require the integration of multidisciplinary scientific knowledge (electrical engineering, economics, statistics, artificial intelligence, signal processing, control theory, applied mathematics).

More specifically, the activities included in this roadmap will consist of:

- Developing a comprehensive, structured overview of the functional and technological building blocks implemented in innovative digital solutions being developed.
- Defining and coordinating scientific work in the fields of Optimisation, Modelling, Simulation, Control and Artificial Intelligence.
- Establishing and coordinating scientific collaborations in these fields.
- Providing expertise in R&D projects, and more broadly to RTE, on decision-support methods and algorithms.

26. https://opensource.rte-france.com/

Annex

Scale for Representing the Maturity of R&D Activities

A maturity scale is defined to track the progress of R&D work carried out by RTE. It is based on a “TRL”[27] level and grouped into four major phases according to the colour code presented in the table below:

Maturity	Technology Readiness Level (TRL)	
01. Exploratory R&D	TRL 1	Monitoring, observation of the basic principle
	TRL 2	Formulation of the technological concept
	TRL 3	Experimental proof of concept
02. Prototyping and concept validation	TRL 4	Technology validation in the laboratory
	TRL 5	Technology validation in a real environment
03. Demonstration	TRL 6	Demonstration of the technology in a real environment
	TRL 7	Demonstration of the system at the prototype scale in an operational environment
04. Pre-industrialisation	TRL 8	Qualification of a complete system
	TRL 9	Real system demonstrated in an operational environment

The mapping of maturity levels to the types of R&D activities conducted at RTE is presented below:

Exploratory R&D
Proof of concept on small-scale cases. We focus on a specific area, formulate the question, define modelling foundations and then conduct initial tests on toy problems.

Prototyping and concept validation
Laboratory validation on cases representative of the operational context (e.g., a simulation is conducted in R&D on a real case). Modelling and exploratory tests are carried out on real problems but remain within the R&D laboratory. At this stage, there is no guarantee that the approach will work in an operational environment.

Demonstration
Validation in an operational context. For software, a prototype is developed and tested in an operational environment (e.g., testing offline at the National Control Centre (CNES)). For a study, a flagship study is launched (e.g., Energy Pathways to 2050, electric mobility, hydrogen) with a good chance that the results can be published by RTE.

Pre-industrialisation
Full operational validation and handover to the business units. For software, tests are conducted successfully, allowing deployment to production. For a study, the flagship study is capitalised on, and all necessary actions are taken (e.g., documentation of the new methodology) so that it can be directly replicated by the business units without R&D intervention.

The incentive regulation budget for R&D covers the first three maturity phases (TRLs 1 to 7).

27. Technology Readiness Levels (TRL) are used to rate technological maturity on a scale of 1 to 9. This scale, first used by NASA, is a benchmark in technology research.

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