



Le réseau  
de transport  
d'électricité

# COLLEGE OF DISTINGUISHED EXPERTS

## The expertise for tomorrow's network

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2022

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# Foreword

**F**or more than a century, the electricity system has been developing and rose to the various challenges of the 20<sup>th</sup> century by drawing on that solid expertise. The 100-year anniversary last year of the creation of CIGRÉ bears witness to the vitality of the international community of specialists in high-voltage electric systems.

RTE, based on the long-established excellence of the electrical tradition in France, can rely on a pool of recognised subject-matter specialists to meet the challenges of the energy and ecological transition. Over the years, this expert knowledge, which was initially centered on electrical engineering, has been enriched in many different ways: from the economics of energy systems to ecology and digital technology.

This pool of subject-matter specialists, embodied in the College of Distinguished Experts (Collège des Emérites), experts among experts, is by definition discreet. In these days of Twitter, of the widespread PowerPoint mania that fosters overly simplistic reductionism, we wanted to give them an opportunity to set out, to share in an instructive format, their view of the contribution made by their specialisms to the challenges facing RTE. That is the purpose of this compendium, which situates these different specialist areas in the bigger picture, and also offers a way of highlighting the very essence of power networks, that it to say, creating links.



**Olivier Grabette,**  
Executive Officer

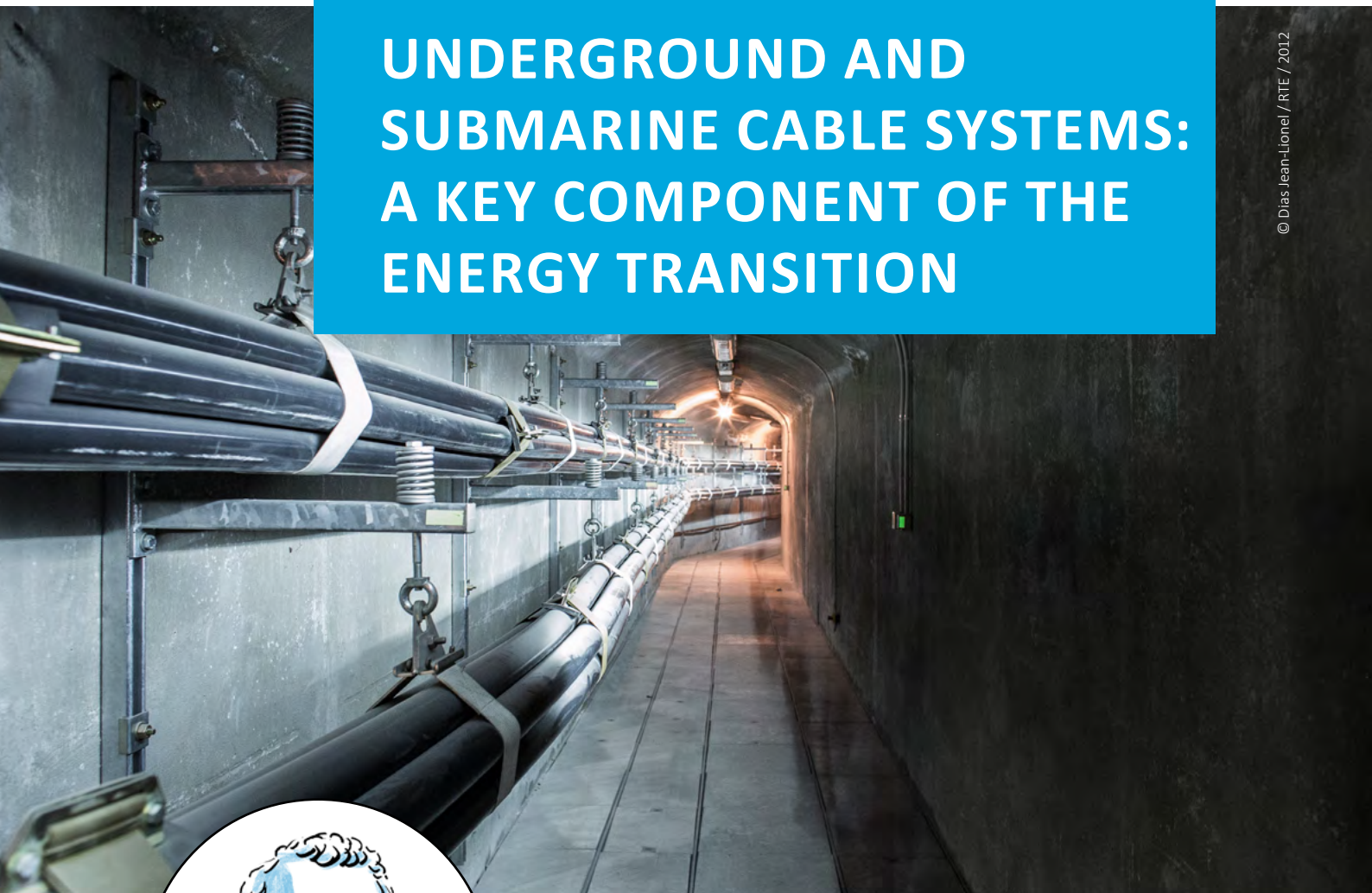


**Sébastien Henry,**  
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# UNDERGROUND AND SUBMARINE CABLE SYSTEMS: A KEY COMPONENT OF THE ENERGY TRANSITION

© Dias Jean-Lionel / RTE / 2012



**Pierre HONDAË** |

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The development of renewable energies, climate hazards, and recent advances in direct current converter technologies, have led to adaptations in RTE and development of its network. These advances entail the construction of underground and submarine systems to link up offshore wind farms or establish overseas interconnections. The network must be characterised by increasingly interwoven connections, that can be operated to allow for maximum capacity.

A “cable system” is made up of terminations, cables, and joints. The difference between a land cable and a submarine cable is the addition of armour around the land cable, both for alternating current (AC) and for direct current (DC). Therefore, when we refer to AC or DC cable systems, this will mean land or submarine cable systems.

A new technology has recently been integrated in the network: offshore installations with dynamic cables. The “offshore dynamic cable” system is comparable to the AC cable system technology but has different functional and strategic features.

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The cable system looks like a straightforward part of the network. But its development and its design draw on many disciplines (electrical engineering, chemistry, thermal design, mechanical engineering). The linear profile of the system and the associated manufacturing processes make it susceptible to any adverse drift in the control of manufacturing parameters. It is therefore essential during manufacture to check on the suitability of the chosen components, their intrinsic design, and their consistent performance.

This susceptibility accounts for the numerous tests that have been developed and have become standard. So-called short-term tests have been supplemented by longer-lasting endurance tests under severe stress conditions with a view to establishing the long-term reliability of the cable system and its full compatibility. It is thanks to this set of precautions, based on painstaking research, that we have both safe and relatively inexpensive AC and DC underground and submarine cables.

The accessories (joints and terminations) developed for AC land use have, for the most part, been reused for HVDC and offshore purposes too. The differences can involve some dielectric fluids for terminations, and the stress-cone for joints and terminations, which are specifically for DC applications. As regards the cable, the difference between DC and AC is only the insulation and its two semi-conducting screen on conductor and on extruded insulation. This also applies to the insulator for the “offshore dynamic cable”. Accordingly, the different equipment specifications are derived from the RTE 214 specifications for land high-voltage AC cable systems.

### AC cables

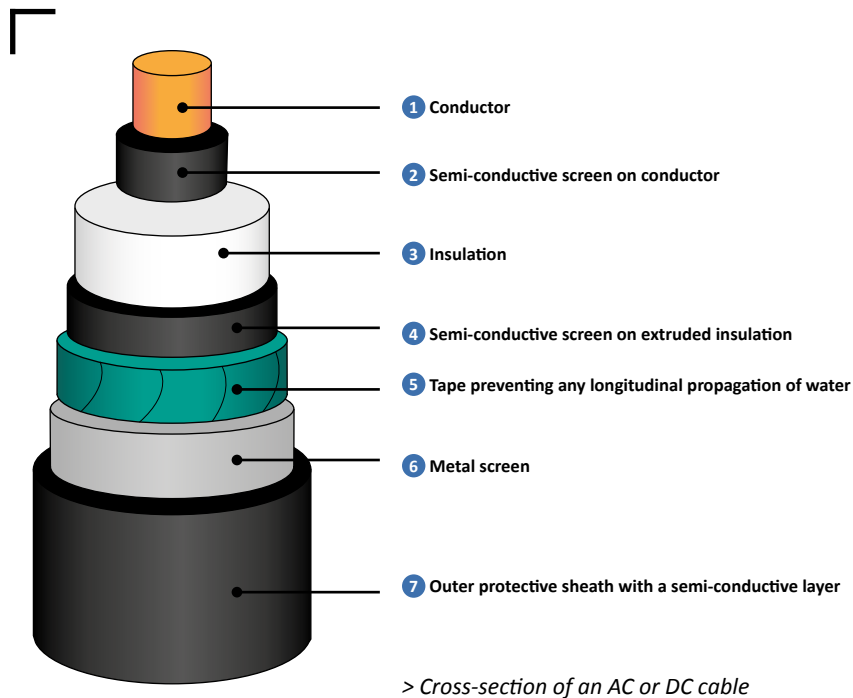
Insulated power transmission cables date back more than 100 years. Two main technologies emerged from the start: impregnated paper insulation cables and extruded insulation cables. From the beginning of the 20<sup>th</sup> century up to the 1960s, impregnated paper insulation dominated the industry. It is now only used worldwide for very high voltages.

In the 1960s, in France, these cables were gradually dropped to be replaced by polymer insulated cables. This change was mostly due to the latter’s reduced need for maintenance, small dielectric loss, higher transmission capacity, and lower cost.

The extruded insulation (cross-linked polyethylene) cables now meet all RTE’s requirements up to the 400 kV systems, by virtue of their unrivalled ease of installation and operation, as well as highly satisfactory reliability.

### DC cables

Polymeric DC cable systems are recent (20 years) and there is limited operating experience to date. Towards the end of the 1990s, significant energy interconnection needs gave rise to high demand for new HVDC connections among the transmission system operators (TSO). But at the time, cable manufacturers and leading laboratories had either suspended or mothballed their R&D work on HVDC systems. R&D had to be jump-started and new laboratories built. It was necessary to validate the new technical stages of impregnated paper insulation cables, with a twofold increase in voltage, and a new design of cross-linked polyethylene (XLPE) insulation for the cables of 320 kV systems.



This validation exercise is not yet complete. A number of unknowns remain with respect to the lifetime rules of direct current. In fact, this gap in knowledge led CIGRÉ to advocate applying the regulations governing the electrical ageing of AC cables with a safety coefficient so as to calculate the testing voltage values of DC electrical cables in order to validate them.

Furthermore, the development of DC cable systems and particularly of the cable insulation and the stress-cones for joints and terminations (a feature of DC compared to AC) is complex. A manufacturer supplying cable systems with insulators operating on alternating current would not necessarily know how to do so for direct current.

### The “offshore dynamic cable” system

Whereas installed offshore wind power has now reached a degree of technical maturity, achieving the full potential of floating wind turbines will entail siting wind farms far from coastlines, on sites more than 50 metre deep, where the complexity and cost of seabed foundations justifies the transition to floating wind power (see box). Although the initial objective

is to overcome the technological obstacles, the floating wind power industry is striving in the long term for economic performance that is comparable to or even better than that of offshore wind power.

### The priorities for manufacturers

Generally speaking, the new AC, DC and “offshore dynamic” cable systems must meet several objectives. Thus, the cable systems must be secure, with fire resistance and blast protection features (protection of assets and third parties). Cables must also be developed to incorporate fibre optics (connected cables).

Lastly, the “offshore dynamic cable” systems must have the proper reliability: these non-watertight cables are designed for a given operating lifetime. It is also important to take advantage of “off-the-shelf” technologies: this means using 90 kV AC qualified land equipment and adapting it to the standards for 66 kV offshore cable systems, to deliver availability (qualification by extension) and better pricing.

## **THE OFFSHORE DYNAMIC CABLE SYSTEM AND THE CHALLENGES OF FLOATING WIND POWER**

According to a report released in 2020<sup>1</sup>, there are 21,000 km of inter-array cables and power cables installed around the world, including more than 12,000 km of offshore wind turbine cables installed in Europe. The 220 kV AC cable system is becoming the standard, but the further it is from the coast, the more reactive power becomes an issue. It is the 66 kV system that is becoming the norm for inter-array cables (approximately 67% of installed cables).

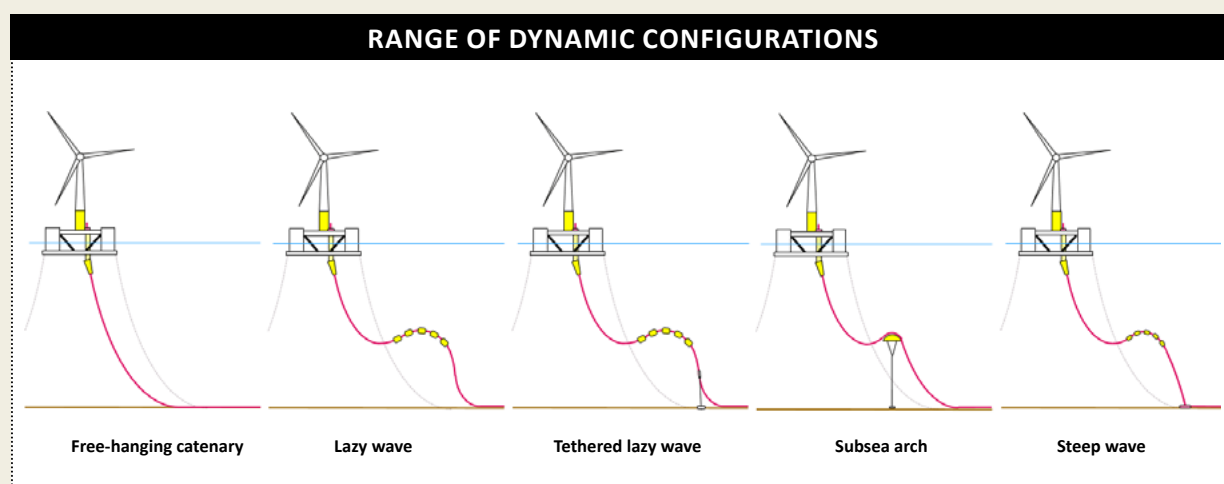
At present, wind power is well established, and this technology has reached maturity. The current trend is upgrading: bigger, more power (>10 MW per turbine, >1 GW for a wind farm) with non-watertight 66 kV inter-array cables, and the advent of direct current.

The next challenge is floating wind power! This technology is needed to fully develop the offshore wind power potential in Europe and beyond. This is especially true for France, where the bathymetry<sup>2</sup> of the most wind-exposed sites often shows that they are not suitable for seabed installation.

For RTE, this translates into floating offshore platforms and 225 kV dynamic cables, a technology that currently requires further development. These “dynamic” cables are designed to flex, in order to accommodate the motion of the floater on the surface of occasionally very rough seas.

The solution lies in installing fittings such as buoyancy modules to the cable, thereby giving the cable a wave-like shape which, like a spring, can “dampen” the movement generated by the motion of the floater. There are several ways of attaching these fittings, thereby changing the shape of the dynamic cable mooring line from the surface to the seabed: these are the different configurations. Every configuration has its advantages and drawbacks, which have to be tailored to fit the individual needs of each project.

Since 2015, several countries, including France, have started constructing demonstration floating wind turbines. The Floatgen demonstrator was set up at Croisic in 2018, and the installation of the Faraman, Groix, Leucate and Gruissan demonstrators is underway. These demonstrators will implement many new designs for floaters, anchors, and dynamic cables. This competitive environment should prove to be a valuable technical learning experience for future 225 kV commercial wind farm fleets.



1. 4C Offshore Report, July 2020

2. Measurement of depth and contours to determine the topography of the seabed



## ○ Different challenges for the different cable systems

With AC systems, the network becomes more complex with the introduction of renewable energies, the increasing number of underground cables, their operation at maximum voltages, and the installation of ever greater numbers of autonomous energy sources. Consideration should therefore be given to the new operating constraints associated with tomorrow's equipment.

In order to prepare for this, RTE must improve even further the synergies and interplay between the internal specifications engineers and the buyers. RTE must systematically, and proactively, initiate current and voltage coordination studies for future projects. The challenge is to ensure better preparation for the installation of new equipment that is compatible, to guarantee interoperability and complete integration into the network, and thus to maintain a high degree of network reliability.

### The importance of TSO cooperation for DC systems

For DC cable systems, the challenges are related on the other hand to the interconnections and exchanges with other European TSOs. The complexity of HVDC technology should prompt RTE to consider the importance of exchanges and even collaboration with other TSOs in different fields such as purchasing, as regards the need for specifications to be agreed during consultations.

Synergies should also be sought in the context of qualification. At present, each cable manufacturer proceeds with its own qualification in connection with one project and therefore with one or two TSOs. But downstream, other TSOs could use this qualification for their own projects, without having contributed financially. It might be feasible to identify a collective need for co-financing a qualification, which would among other things establish a common baseline of requirements.

In terms of asset management, cooperation could improve the sharing of operating experience among the TSOs, allow for the pooling of some resources, facilitate forward planning for obsolescence issues, and prevent too much dependence on manufacturers.

One final opportunity for exchange: simulation. This constitutes a key resource for operating complex

components with a level of expertise appropriate to the technical challenges arising from the energy transition.

As regards the insulations, study results could radically affect the use of existing and future cable connections, as well as tomorrow's purchasing strategies. The insulator for existing RTE cable systems is operated at up to 70°C (manufacturers' warning). However, new test results indicate that there is a safety margin for temperatures above 70°C, perhaps even 90°C. Other materials are also being investigated and may deliver alternatives or improvements to the XLPE currently in use.

The technological choice made by RTE and many other TSOs was XLPE. This material is well known, with highly satisfactory operating experience. At the present time, if the company wishes to move towards other types of insulation (particularly for high-stakes projects such as interconnections), then a risk-benefit analysis must be conducted.

Lastly, for the cable companies, the R&D issues must be taken into account. Each manufacturer develops its own accessories, and manufacturers have not set up contractual partnerships to put forward better systems. Furthermore, they are not necessarily ready to develop specific accessories to guarantee successful HVDC system operation.

### Offshore power facing the same challenges as DC systems

There are currently no floating substations or 225 kV voltage dynamic cables in service anywhere in the world. There are many technological challenges. Another challenge is the distance between the offshore fleets and land. The HVDC dynamic cable could help to cope with reactive power, but here again there are simultaneous constraints (thermal and electrical fatigue) and a lack of know-how.

Further research is therefore needed, and possibly a review of the cable qualification strategies, which are currently devised separately: mechanical performance on the one hand, and thermoelectrical performance on the other. For the TSOs, it will be important to enhance their understanding of the mechanical characteristics of cables and of floater dynamics - topics at the heart of naval engineering.

## **PRE-STANDARDISATION AND STANDARDISATION: A VALUABLE PRESENCE**

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With AC systems, the standardisation of cable systems stems partly from the joint development work by EDF R&D and three French manufacturers: Nexans, Câbles Pirelli and Sagem (Silec). From the 1980s onwards, over a period of 30 years, EDF and these three cable manufacturing companies played a crucial role in ensuring that the polymeric AC cable was recognised by the international community as a whole. A recognition that began with EDF's specifications, progressed to French and then international standardisation, and resulted in applying the testing standard that helped develop today's "French" standard cable.

Since 2008, RTE has updated its cable system specifications as and when required by the need for changes to the network. This flexibility, and this autonomy from external players, must be maintained long term, while bearing in mind that specifications rely to a significant degree on tests derived from international standards that are updated at a slower rate than those of the networks!

### **Aiming for ever-greater requirements**

Equipment has to be as standardised as possible. This is one of the reasons why it is vitally important for RTE to take part in the pre-standardisation and standardisation groups in order to influence the decisions on amendments to the requirements. RTE is one of the few TSOs in the International Electrotechnical Commission's (IEC) Working Group 16, which oversees cables. Most group members are cable manufacturing companies: whenever RTE puts forward a well-argued technical point, the cable manufacturers around the table are torn between keeping the less demanding requirements or aligning with a TSO to raise requirements. The participation of other TSOs in the working groups on maintaining cable standards would help to raise the technical requirements.

HVDC cables have been standardised by the IEC since 2017. RTE's influence in the forums addressing standardisation meant that a standard was drafted soon after the installation of a 320 kV HVDC polymeric cable link between France and Spain (a world first).

Here again, RTE plays a prominent role in the working groups tasked with standardisation, but very often stands alone before the cable manufacturers. There are few representatives, or none, from the other TSOs in some of the important working groups that are setting the specifications for equipment and issuing testing requirements. The equipment qualification tests are often minimum requirements. Like RTE, the major TSOs make up for this by producing their own specifications, but it then becomes difficult to impose them on the cable manufacturers, as they depart from the standards.

This imbalance in representation vis à vis the manufacturers during the process of standardisation is a reminder of the importance of the TSOs' participation in pre-standardisation forums (CIGRÉ), to pave the way for drafting a standard and to produce a document that itself establishes the highest standards.

Within CIGRÉ, RTE is very active in Study Committee B1 for insulated cables (SC B1). Its extensive involvement ensures it is seen as a rightful and recognised player in the world of cables, particularly in relation to its suppliers. Unlike the participants working on setting up standards, SC B1 operates more as a group of peers. There is no power imbalance, and the organisation is truly independent. The lead pair at the helm of the committee carefully maintain this balance: tradition dictates that the Chair is held by a cable manufacturer and that a TSO representative acts as Secretary.

Once again, questions are likely to arise regarding cooperation between TSOs, particularly in relation to maintenance at sea, and the benefits of pooling repair resources, and as a result, standardising technologies (development of repair joints that are interchangeable between cables).

Compliance with the commitments made at a European level in relation to renewable energies will be achieved through the development of offshore

wind farms. These wind farms will require high-voltage submarine cables. Their development is therefore closely linked to Europe's commitments on CO<sub>2</sub> reduction and requirements for offshore cable connections.

As for underground cable systems, they continue to provide a better way of promoting acceptance of the network, at a time when the issue of visual impacts on surrounding landscapes has never been more topical.



### Further reading

- **Dossier sur les câbles électriques de puissance (A review of electrical power cables)**, La Revue de l'Électricité et de l'Électronique (Electronics and Electricity Journal) - REE 2021-1

# THE TRANSFORMER, A ROBUST PIECE OF EQUIPMENT WITH A FRAGILE INDUSTRIAL BASE

© Lafontan Mikael / RTE 2016



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RTE relies on a narrowing network of manufacturers for its supply of transformers. An industry fragility that may prove to have significant medium- and long-term consequences for the company, which does however have some levers of action.



The term transformer covers many items of equipment with one common operating principle: electromagnetic induction. The RTE fleet is essentially made up of large power transformers. Then come the medium power transformers, followed by other equipment governed by the same set of standards.

Large power transformers (LPT) are defined in European regulations as equipment with a rated power of more than 3 150 kVA or more than 36 kV. This very broad category encompasses all the power equipment used by RTE. They are all very similar in design. At present, approximately 1 300 LPTs are oil-immersed transformers.

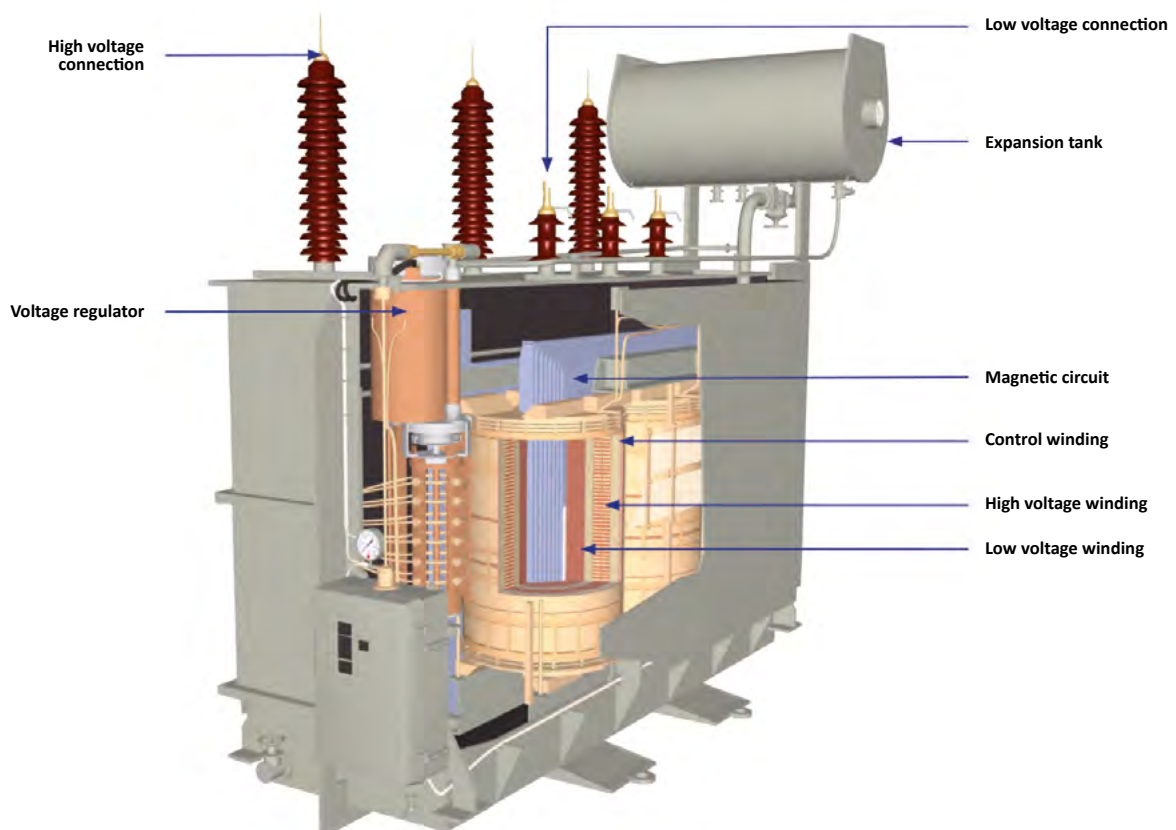
Medium power transformers (MPT) have a voltage rating below 36 kV and a power rating of less than 3 150 kVA. Auxiliary service transformers belong to this category. Though based on the same principles of physics, these transformers have particular manufacturing features linked to their lower power ratings.

The term transformer also applies to special transformers, namely the phase-shifting transformers, booster transformers and rectifier transformers, that are used in HVDC converter stations.

Lastly, the liquid-immersed reactors, whatever their uses (shunt reactors, series reactors, smoothing reactors), fall under the same family of standards as power transformers. This equipment follows the same design rules as the transformers.

Instrument transformers, with resin insulation and a toroidal core, are technologically too far from the power transformers to be grouped with them.

#### CUTAWAY VIEW OF A TRANSFORMER



## ○ An industrial base less adapted to RTE's needs

Transformer manufacture is a highly competitive sector with low profit margins and high risks (the slightest defect has cost implications for the manufacturer; manpower; even raw materials). For almost four decades, we have been experiencing a dual trend. On the one hand, a concentration of supply from the manufacturers, with the disappearance of many production sites, and on the other hand, a concentration of manufacturing plants in the hands of a few big players.

At the same time, manufacturing plants no longer specialise in a particular market as was the case for many years, but rather in a particular product, with a view to optimising the manufacturing process. This has resulted in less customisation of the supply, and a need for enhanced qualification.

### Large power transformers

Depending upon the category of transformer, the industrial context varies as the know-how differs. LPTs<sup>1</sup> draw on significant technical skills and require a great deal of research work by design departments. Few transformers are produced every year (from 30 to 100 units) and the average series consists of 5 transformers. In addition, the rationalisation of production plants has made them less adaptable.

The major players have retained production units in order to be able to offer sets of transformers on a “turnkey” basis. For their part, smaller manufacturers owe their market share to more attractive pricing, though they are not always able to deal with the consequences of possible defects.

Economic pressure and improved design tools have helped reduce design margins, and transformers are therefore more sensitive to manufacturing tolerances and to the quality of the materials used. In fact, the effects of the Covid-19 crisis highlighted that transformers are highly sensitive to fluctuations in the cost of raw materials.

We are also seeing a loss of skills and experience among manufacturers, brought on by the merging of R&D teams, the departure of long-established specialists, and more job-hopping by the younger generation. Additionally, more and more activities have been relocated outside France and outside

Europe. In the 1980s, there were 5 large power transformer manufacturers in France. Only one survives today.

### Medium power transformers

Compared to the LPTs, MPTs call for less technical know-how and fewer industrial resources. The majority of the world market consists of transformers bound for power distribution companies, with the remainder focused on special industrial equipment. Only a very small proportion of the distribution transformers are destined for power transmission substations.

The supply of distribution transformers is split between large-scale enterprises producing very-high-volume standardised products, and SMEs producing customised products in small quantities. At the present time, this sector is not a concern, and new producers can easily emerge, even if close attention must be paid to safety and quality.

Regarding transformer equipment (including very specific equipment), the industrial supply does not appear to face any immediate threat. However, most of the equipment that was produced in the country until the 1990s has now seen its production relocated. Among the major items of transformer equipment, on-load tap changers are no longer manufactured in France, and French production of bushings may come to an end as a result of changed technological preferences across world markets (see: Regulation, standardisation: advocating for RTE).

### Quality and economic incentive

The majority of manufacturers have made drastic reductions in their workforce. The failure to replenish the pool of technical specialists, and the quest for financial optimisation, have very significantly diminished the bank of experience of the designers. In the course of design reviews, RTE has noted worrying errors, even by manufacturers considered to be experienced.

The transformer is a product for which experience is the best guarantee of manufacturing quality. Many design and manufacturing stages rely on transferring the knowledge acquired over time and passed on

<sup>1</sup>. LPT considerations also apply to liquid-immersed reactors

mostly through mentoring. The construction of large power transformers is mostly a manual process. The judgement and know-how of the operator are crucial to maintaining the quality of the product, which underscores the need for RTE to exercise the highest degree of vigilance.

Owing to its technical expertise, RTE has long been the benchmark for suppliers who could take pride in having the company among their customers. Today, this is no longer the reasoning of manufacturers, who are focusing instead on selling price, volumes, and lesser requirements. RTE's requirements are therefore sometimes out of step with the industry offer. For example, RTE sources very small quantities of MPTs (fewer than 30 a year), stipulating an unusual design feature linked to their use (inner partitioning) and a specific environmental requirement (low viscosity plant-based ester). These transformers must be extremely reliable as they are directly connected to the tertiary terminals of transmission equipment without a circuit breaker, and any fault leads to the loss of the power transformation system to which the auxiliary service transformer (AST) is connected. RTE must therefore be exacting with regard to design and manufacturing quality, and reliability. At the present time, few manufacturers are able to meet these requirements.

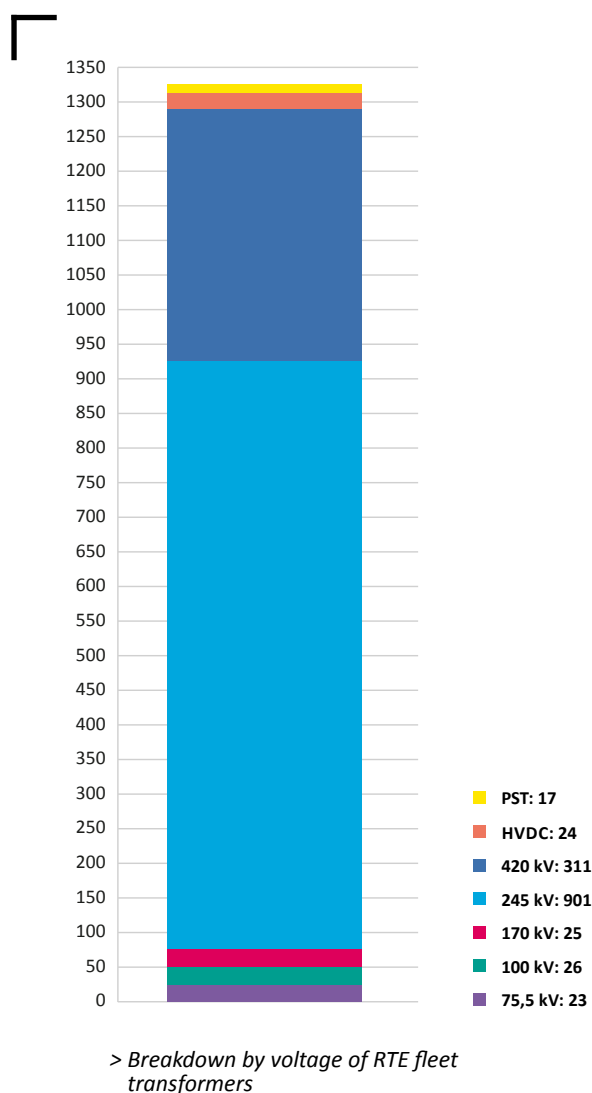
### The risks from European deindustrialisation

Preserving know-how in Europe is a real challenge, since it is likely that by the time users are faced with the need for widespread replacement of equipment installed in the 1960s and 1970s, there will no longer be any European production sites capable of meeting their needs. Through the demand from European transmission system operators (TSO) is likely to increase over the next 15 years, there is a risk that the supply will continue to contract and to be centralised in a few countries: Germany, Italy, Croatia and Slovenia. It is becoming more difficult to keep production sites working, and the corporate owners of these plants have all invested heavily in Asia (and China in particular), where they have production capacities in excess of local demand, and benefit from low labour costs.

In order to guarantee its supply capacity without becoming dependent on Asia, RTE can help keep some European plants working by entering into long-term partnerships that enable them to invest. A minimum annual volume of orders would probably be required for these partnerships.

RTE can also influence the industrial landscape through its political and technological choices. Without strong initiatives, supplies may be under threat in terms of lead times, quality, and cost. Through action, possibly coordinated with the other TSOs, RTE is in a strong position to maintain a European industry. For their part, the manufacturers will have to meet product quality requirements and remain financially secure.

Lastly, with regard to major LPT projects such as offshore cable connections, purchases for RTE's central stock of equipment (so-called "national stock") in preparation for upcoming projects could prevent long gaps in work schedules and ensure reliable delivery times.



## GROWING TRANSPORT PROBLEMS

A transformer is a heavy and bulky piece of equipment (180 tonnes in weight, 10 metres long and 4.5 metres high) and RTE is confronted with transportation problems. Present conditions do not guarantee the transport of equipment needed in the event of increased failures or faster replacement operations in the fleet. The company is currently facing significant challenges in obtaining transport authorisations (to cross bridges, pass through towns). It is not possible to carry out more than 30 transport operations per year.

Looking ahead to the replacement of equipment, work is needed to obtain transport authorisations. For this reason, cooperation with transport companies is essential.

## ○ Regulation, standardisation: advocating for RTE

European regulations have led to increased equipment mass and size. The European Commission regulated transformer losses in a bid to drastically reduce their energy consumption, which resulted in increasing their mass.

The establishment of these regulations is the result of lobbying by the union of copper producers, by steelmakers and by manufacturers in particular. The users' point of view, though generally known, has little weight compared to the economic interests of industry. Despite this, the TSOs have succeeded in obtaining energy efficiency goals that are sustainable within reasonable timeframes, by contributing their knowledge of the entire life cycle of transformers. TSOs like RTE are the only ones to have the data needed to monitor their ageing process and anticipate failures.

If authorised losses are to be reduced once more for large power transformers, the risk lies in the TSOs diverting a large part of their investment in return for small energy gains. Transformers represent only 10 % of transmission network losses.

RTE's sustained engagement with national and European bodies is therefore the only means of influencing decisions that may prove to be costly and not very effective. Coordination with the other TSOs is also essential.

### Diminishing requirements

Likewise, RTE's presence in standardisation bodies is vital. The set of standards (IEC 60076) governing transformers is being fully redeveloped, and many competing interests are driving down the level of requirements and complicating the formulation of the standards. The introduction by default of minimum standard clauses forces users to set specifications above the standard in order to guarantee the reliability, the fitness for purpose, and the service lifetime of the equipment. These requirements above and beyond those defined in the standard are then seen by the manufacturers as unjustified and costly. Strong manufacturer representation in these bodies may threaten RTE's practices.

Major work is underway with regard to maintenance of the liquid dielectrics in service, the aim being to prescribe requirements for in-service performance and frequency of liquid analysis. These issues can potentially lead to RTE being held responsible in the event of failures, and exonerate the constructor from its responsibility.

The general standardisation of equipment also threatens RTE's policy of holding a central stock of bushings, and could jeopardise the benefits of 60 years of substitutability obtained thanks to the compliance of bushings to the French standard. Indeed, there is no prospect of this standard ever being adopted at an international level, and bushing manufacturers are generally against worldwide substitutability, since some have built their profitability on a capacity to supply tailored units.



Furthermore, in tax matters, the flat-rate tax on network businesses (IFER), applicable to basic transformers, is shifting the technology towards three-phase transformers which, for the identical service, attract one-third of the tax on a bank

made up of three single-phase transformers. When all the stakeholders in Europe are pushing for technologically neutral provisions, it is the tax system that is influencing choices. RTE could point to the importance of French tax neutrality.

## Innovation and development

The transformer is a mature product that for decades has not seen any profound change in its design and manufacturing principles. In the medium term, this equipment will undergo more improvements.

In terms of technology, the challenge revolves around noise reduction, which will simplify installations by eliminating the need for concrete noise-barrier enclosures. The concrete enclosures currently in place involve extending the base of the bushings, making any earthquake resistance impossible for installed equipment. Noise reduction initiatives will pave the way for earthquake resistant equipment.

Digital technology basically improves design tools. The digitisation of substations will only have a marginal impact on transformers, mostly in respect of interfaces.

### Renewable energies, monitoring, and environmental impact

Renewable energies are changing the way in which the power network is being used. With the advent of significant production connected to the sub-transmission<sup>2</sup> network, transformers are having to operate as step-up transformers. This type of operation, unspecified for the majority of the fleet, can lead to the transformers overfluxing, giving rise to hot spots, both in the magnetic circuit and in the windings, to vibrations, and to much greater noise levels than those measured in the factory. All these phenomena can reduce the service life of the equipment, especially if it is being operated near its rated power. Monitoring should prevent some failures. But we must be vigilant with this monitoring: among other things, it will add components with shorter service lives than those of the transformers.

Lastly, one area for improvement is reducing the environmental impact by facilitating recycling

## THE AGAT PROJECT

The Transformer Assets Management Improvement (Amélioration de la Gestion des Actifs Transformateurs, AGAT) project was launched in 2019. It has two components, one aimed at existing transformers, and the other at future equipment.

With regard to the existing transformers, **AGAT** presents a risk assessment that proposes rules of viability. These rules, in tandem with the costing (financial costs, costs related to constraints, corporate image cost) of the consequences of a failure, provide a means of reviewing operating practices. The aim is to come up with new policies for mid-service-life preventive replacement and full overhaul, with a view to extending or reaching the predicted service life of the transformers.

As regards future transformers, the project includes a study on adapting and optimising the definition of transformers to reflect tomorrow's requirements and conditions.

Aside from **AGAT**, other projects are addressing advanced functions that can provide input to monitoring rooms, or are looking at the monitoring of in-service equipment.

and promoting the use of new bio-sourced and biodegradable synthetic hydrocarbons<sup>3</sup>. These liquids look promising and could count against the use of flammable natural esters like those used for ASTs.

In the long term, the future prospect for transformers is their disappearance. It is reasonable to expect a

<sup>2</sup>. Sub-transmission relates to regional transmission networks with limited voltage. In France, this essentially applies to the 63 kV et 90 kV lines.

<sup>3</sup>. These liquids are currently subject to the domestic tax on petroleum products (TICPE).

## CLIMATE CHANGE: THE IMPACT OF HEATWAVES

Transformers are pieces of equipment that are not sensitive to wind, and their installation protects them against flooding. However, they can be sensitive to higher temperatures.

A rise in peak temperature to more than 40°C for periods of more than 90 minutes<sup>4</sup> will cause a reduction in power. This would be a 10 % reduction if the temperature reached 45°C. The increasing number of heatwaves will also invalidate the overload protection regulation systems, which currently disregard periods with ambient temperatures above 30°C.

The increase in average annual temperature has no direct effect on the transformers in the RTE fleet, as the latter are specified for an average value of 20°C which is not expected to be reached in mainland France. However, the consequences for thermal ageing are more difficult to assess.

Though it is still possible to reduce transformer capacities during spikes in hot weather, in the longer term it will be necessary to consider the specifications for new equipment.

gradual reduction in electromagnetic transformers in favour of static converters. There has been a start on broadening the existing standard to pave the way for technological neutrality in regulation, as a means of including these new technologies. The future is therefore taking shape with power electronics. At the present time, power electronics is not efficient enough, but the sector is developing at a rapid pace.

It is worth noting that despite repeated promises and conclusive trials, the superconductive transformer does not seem able to compete with existing technologies in the medium term. Trials have been carried out only for proof of concept, and no long-running project has yet been created.

Pending the disappearance of the transformer as we know it, it is important to keep the industrial base alive. RTE must be able to make forecasts of requirements and provide an outlook to manufacturers. The convergence of the French recovery plan and the government's intention to reindustrialise the country, while greening its economy, can create leverage for the replacement of old equipment and foster a certain national bias. Finally, the European TSOs must do more to reach consensus on their requirements and on suitable joint responses.



### Further reading

- **Le transformateur de puissance (The power transformer)**, B. Hochart - Technique et documentation-Lavoisier (1988)
- **Transformers Magazine**, Merit Media - Quarterly
- **CIGRÉ brochure**, produced by the A2 Committee
- **The J & P Transformer Book: A Practical Technology of the Power Transformer**, Franklin, Franklin et Heathcot - Newnes, 12<sup>th</sup> Edition (1998)
- **Electric Power Transformer Engineering**, Collective work - CRC Press (2012)

<sup>4</sup>. Standard time constant for network equipment

# INTEROPERABILITY, THE KEY TO THE FUTURE SUBSTATION PROTECTION, AUTOMATION AND CONTROL SYSTEM

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Bay Protections and Functions

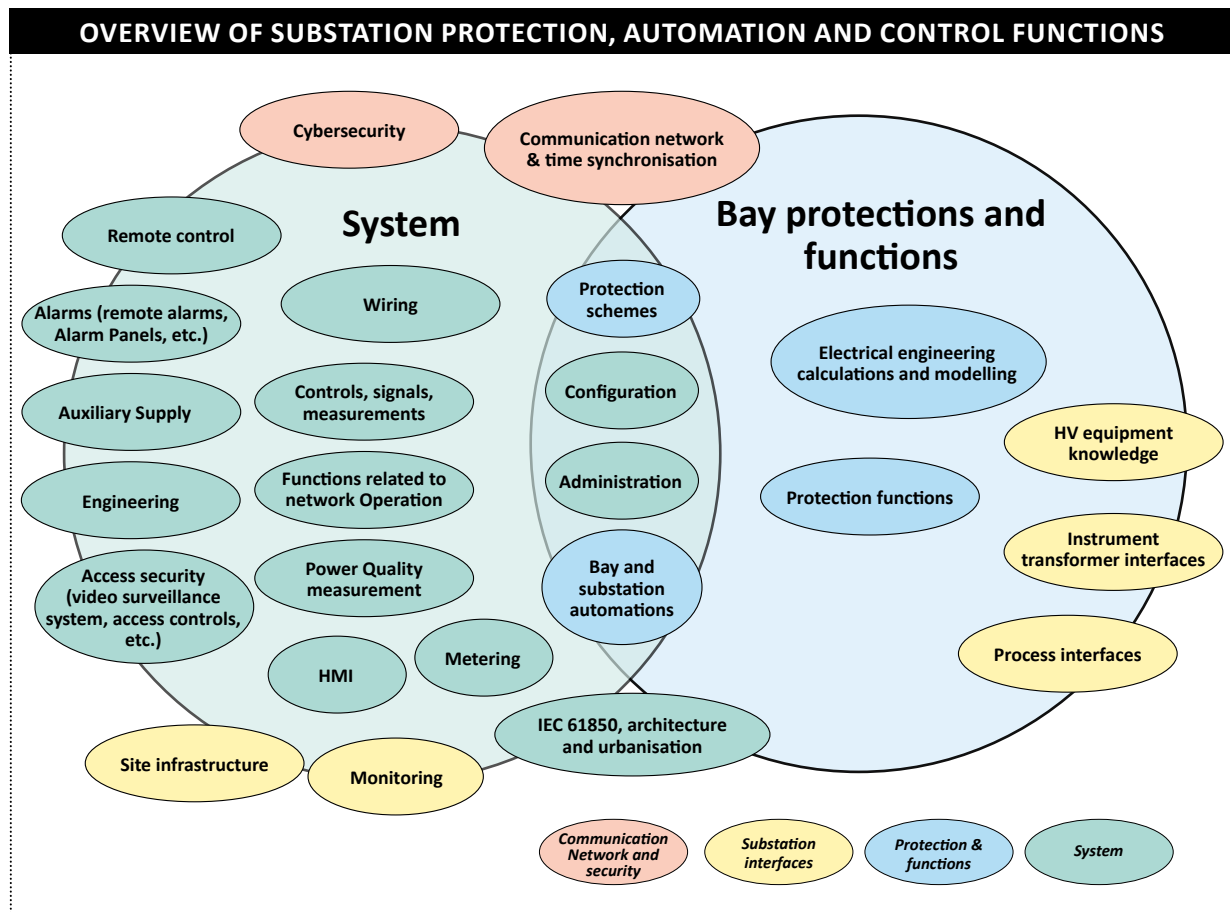


There may be a tendency to confine the protection, automation and control system of an electrical substation to its 3 basic functions: protection, supervision, and control. But as the interactions between these protection, automation and control functions continue to grow, it has become necessary to have a comprehensive view and a systematic approach to the functions, no longer just of the control system, but of the substation itself.

Protection, Automation and Control can be divided into two main areas: bay protections and functions, on the one hand, and on the other hand, all the remaining functions grouped together under the umbrella term “system”. These 2 areas, which go hand in hand, are highly interconnected but also interfaced with other fields of expertise such as high-voltage equipment, communication networks, cybersecurity, etc.

The subject of “bay protections and functions” covers the specialist field of electrical engineering, protection functions, bay controller functions (recloser, etc.), and the interface with the electrical process. The subject of “systems” encompasses the remaining functions in an electrical substation, and guarantees

the overarching architecture and urbanisation framework. The IEC 61850 standard (which covers modelling, configuration, and communication within an electrical substation) binds these two subject areas together.



### From PACS 1.0 to PACS 4.0: decades of transformation

As with industry as a whole, the substation Protection, Automation and Control Systems (PACS) system have undergone several changes. The trend for the mass deployment of “turnkey” systems, based

primarily on the precept of obsolescence of previous technologies with systems that have almost identical functional scopes, is being replaced by a need for “industrial made-to-measure”. Made-to-measure meaning adapted to the requirements of each electrical zone. The timeline of these changes can be summarised as follows<sup>1</sup>:

1. The dates given correspond to the timescales for development, with deployment then potentially spanning longer timeframes, the service life of PACS being of the order of 25-35 years.



**PACS 1.0 1946 - 1970:** Wiring (copper) executed direct by suppliers, on a case-by-case basis.

**PACS 2.0 1970 - 2000:** Industrialisation of wiring, in France represented by the technological systems from Ariane to Daphné, with the development of in-house skills at EDF, and the definition of standardised bay wiring schemes. Thus, with Daphné, a bay control cubicle has a standardised wiring interface, facilitating its integration whoever the supplier of the cubicle. Up to the 1980s, protections and control systems were essentially based on electro-mechanical technology, using relays and point-to-point wiring for each signal. The protections then benefitted from developments in electronics (the “static” stage) and then processors. Digitalisation also helped broaden and complete the bay functions implemented in bay computers. Substation digital communication networks began to be used in the 1990s.

**PACS 3.0 2000 - 2020:** Electronics, computing and telecommunications gave rise to the creation of digital control systems and the Electre technological stage. These are “turnkey” systems. They are based on generic specifications that cover most of the functions required in an electrical substation, so that their customisation is largely achieved through configuration. These systems are “closed” and supplier-designed (each supplier’s system therefore having its own architecture and design) and their capacity to evolve can be limited either by constraints related to their design, or by the supplier’s roadmap.

Potential upgrades are costly (often having to be adapted to different suppliers’ different versions) and take a long time. These systems are no longer suitable if considerable customisation is required.

**PACS 4.0 From 2020 onwards:** The strong foundation, the maturity, and the completeness of IEC 61850 create new opportunities. The hope for interoperability between the equipment of different suppliers, difficult to accomplish with the first systems in the 2000s, or only attainable by dint of great engineering effort, is now within reach. Equipment for the digitalisation of electrical process information, which can be installed near to the switchgear itself, are available, making it possible to remodel the PACS architecture. However, this remains an open standard, with both mandatory and optional parts, which may lead to different implementation decisions from one supplier to the next.

In order to acquire a flexible and evolving protection, automation and control system, RTE has made key decisions. The company has created its IEC 61850 profile, thereby giving suppliers an interoperability framework. It has opted to be the designer of its system and to define a modular and evolving architecture. Lastly, RTE has committed to the development of functions that enable rapid customisation of the system. The **R#SPACE** project was born.

## ○ The R#SPACE concept

**R#SPACE** allows RTE to have a long-term vision without being constrained by the technological steps that are not interoperable. With **R#SPACE**, whether physical or virtual, the functions will keep the same interfaces and the same mechanisms for exchanging data. Though first envisioned in the early 2010s, the project was launched in 2018 for operational deployment in 2023.

**R#SPACE** reallocates the roles of the industrial players in the sector. At the present time, there are 3 main categories of contractors for PACS . The supplier is responsible for the design and manufacture of the PACS equipment. The system integrator deals

with the design of the cubicles, the integration of equipment into the cubicles, and on-site testing. Finally, the installer oversees the installation of the cubicles, the cable pulling, etc.



With the advent of digital control systems (PACS 3.0), some of the past suppliers of equipment for the PACS 1.0 and 2.0 systems have also become system designers. They design “turnkey” systems, based on standard IEC 61850 or not.

The system integrators bring significant added value to RTE through their involvement, from the very first industrial wiring systems, with the design of the PACS cubicles and their knowledge of substations.

With **R#SPACE** (PACS 4.0), RTE becomes the system designer and integrator. The supplier is once again the supplier of stand-alone equipment. A role of cubicles designer is created to set up the switchboards.

Lastly, **R#SPACE** creates the role of operational system integrator responsible for configuration, factory acceptance testing (FAT) and site acceptance testing (SAT). This is a crucial role, as this system integrator will have the same knowledge as RTE of the architecture and integration of the whole system, and its set-up in the substations.

The project has also provided an opportunity to open up to new players who could not previously submit offers when the tendering was for a “turnkey” PACS: supplier of off-the-shelf SCADA<sup>2</sup> software, suppliers of network switches, etc.

## ○ Standard IEC 61850: the key to interoperability

Released at the end of the 1990s, the IEC 61850 standardised the exchange of data between the PACS components. After a development and implementation phase, IEC 61850 is now a globally recognised standard, widely used in PACS around the world.

To take advantage of the full potential of the standard, and to simplify the specification and testing of multi-supplier systems, it is necessary to combine it with “product” profiles and standards that are mutually coordinated and compatible. This will make it possible to gradually reach intrinsic functional interoperability, for example between instrument transformers and protection functions, or between protection functions and bay automations.

The development of IEC 61850 was driven by Working Group WG 10 of the International Electrotechnical Commission’s Technical Committee TC 57, in which RTE is involved and makes significant contributions. The situation is less homogenous for “product” profiles and standards. For example, for instrument transformers, whose standardisation is headed by TC 38, the IEC 61850 interface is standardised (IEC

61869-9). For protections, whose standardisation is headed by TC 95, work has only just begun and will lead to the delivery of a document, as a first step, which will then have to be transposed to standardising documents containing the general requirements for each protection function. For this, the specifications developed for **R#SPACE** can act as a guide.

Furthermore, CIGRÉ’s B5 Study Committee acts as a forum for sharing operating experience and different approaches.

With its significant and well-coordinated contribution to Technical Committees 38, 57 and 95 of the IEC, and within CIGRÉ, RTE has the means to perform the necessary coordination to move towards intrinsic functional interoperability based on the standards. Thanks to the **R#SPACE** project, and in light of the operating experience from the “Postes Intelligents” project, RTE is in a legitimate and credible position to put forward guidelines for the “product” profiles and standards, as well as updates or additions to the IEC 61850 standard itself.

<sup>2</sup>. Supervisory control and data acquisition

# MOVING TOWARDS PACS 5.0



**Jean-Marie BOISSET** | Distinguished Expert, Local Automation and Control - System

**The three strands of the transition - ecology, energy and digital - are contributing to the transformation of the electrical transmission network so as to enable adaptation to fluctuating electricity demand while guaranteeing balanced networks. The substation's protection, automation and control systems will have to support this transition by supporting more detailed management of the services provided.**

The traditional and indispensable functions of a substation control system are protection, service restoration, supervision, and control (of HV installations and automatic controls). But new requirements and new constraints impose a review of these conventional functions.

Consideration should be given to automations that can easily be customised for flexibility in network operation. Additional functions for remote operability should also be envisaged to improve the effectiveness of maintenance. Monitoring assets (HV and PACS assets) for purposes of asset management becomes essential, as does cybersecurity by design to protect the industrial information system. In addition, eco-design is now an indispensable component.

The substation is an electrical node: the PACS must now be a digital data node, not for mass redistribution of the collected data, but to make the most of the computing power installed in order to judiciously pre-process the information and transmit just what is needed.

This focus on the PACS itself must not obscure the substation's other components involved in protection and control as a whole. Thus, it is also necessary to have an understanding of the auxiliary supply, access

controls, intrusion and video surveillance systems, quality measurement, metering, equipment related to substation operation, and even the monitoring of site infrastructures. These elements are currently managed as separate components, or as components with few interfaces between them. But a systemic approach would help streamline requirements (power network, time synchronisation) or improve the interactions between functions (systems locking in response to an intrusion).

## **The target: the virtualisation of PACS**

**R#SPACE** is designed both for physical and virtual IEDs. The virtualisation of protection, automation and control functions means locating these functions in servers instead of in protection or control IEDs<sup>3</sup>. The functional interoperability thus guarantees independence from hardware.

At the present time, there is an enormous variety of different versions of equipment, and equipment from different suppliers, across the installed fleet of control systems. Managing this fleet is increasingly difficult, as the time to market for a new card or a new piece of equipment is much shorter than the service life of a system in operation.

3. IED: intelligent electronic device: any "intelligent" and thus smart equipment in a substation control system.

Virtualisation addresses this issue. All the protection, automation and control functions can run on some standardised servers, thereby delivering material and energy efficiency. Only the acquisition/transmission modules, interfacing the electrical process, are still dedicated IEDs. Steps should however be taken to make them as efficient, reliable, and resilient as possible in order to avoid complexity of management.

Virtualisation will also streamline training logistics, eliminating the need for multiple platforms corresponding to the different suppliers. It will also make it possible to conduct actual laboratory tests of the functional or database upgrades for an operating site.

The prototyping of the virtualisation of a complex protection function (in a laboratory) is now up and running. The next step is to see the process through to the end and ensure that all the functions of virtualised instrumentation and control are operating correctly.

### Two possible routes

The first route is to virtualise the IEDs. Suppliers create an “as-is” virtual machine of their IED, with an identical functional scope. For example, the **R#SPACE** system communicates in the same way with a virtual IED as with a physical IED. The system can therefore be a hybrid, combining physical and virtual IEDs.

This option is probably the quicker, so long as it is taken up by the suppliers. It is not just a technical issue but also an economic one. This raises the question of the physical platform supporting the virtualised IEDs of all the suppliers. The option of a structure provided by RTE (or a third party) is under review, but imposes major implementation constraints.

The second route is to remodel the urbanisation of the protection, automation and control system in order to avoid creating a “virtual carbon copy” of the existing system. For example, why reapply the concept of a bay calculator, strongly associated with the PACS bay cubicle, and which does not exist anymore? Is it at all useful to create a synchrocheck recloser<sup>4</sup> in each “bay” when at present one site synchrocheck recloser is adequate, owing to single point of control?

This second option makes it possible to redefine a control system in more general terms, and to open the door to new players. It must not however lead to a complete revision of all the functions. A mix of “supplier protection IEDs” (minimising the risks associated with these functions) and “re-urbanisation of the supervision/control system” may provide the optimal solution.

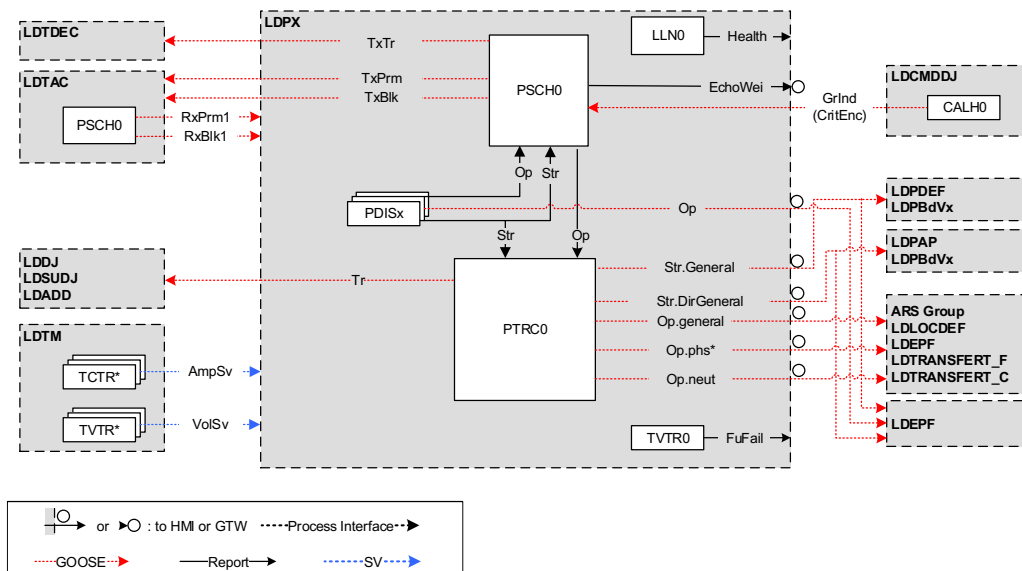
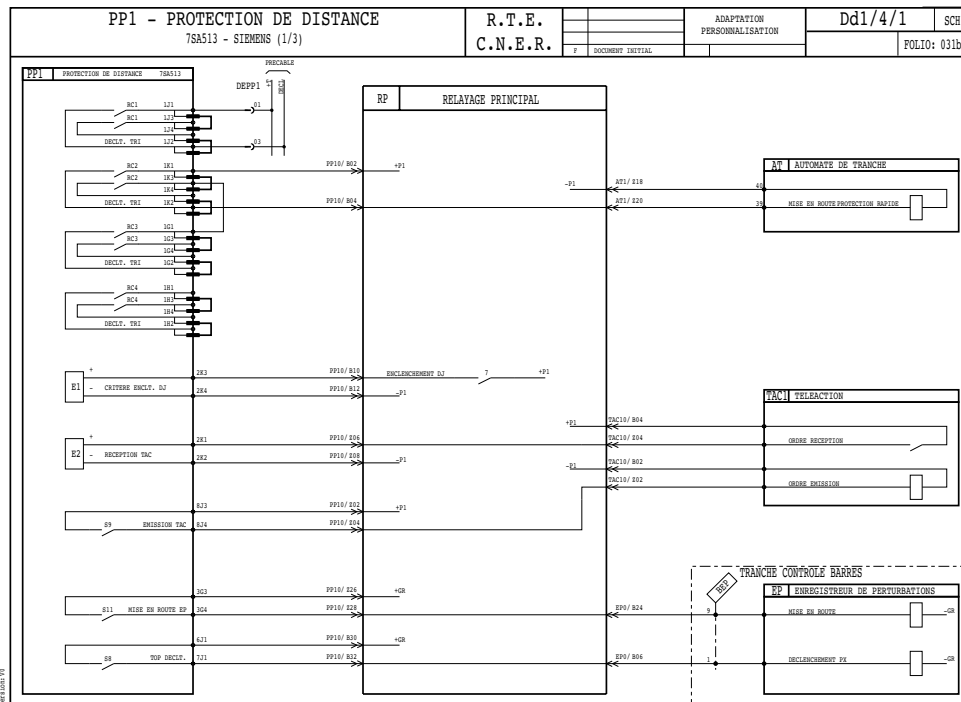
Whatever the route taken, one key feature is the development of a virtualisation platform that can host virtual machines supported by different horizons. The strategy of open-source development of such a platform is the first step towards instrumentation and control system 5.0, part of the **SEAPATH** project at the Linux Foundation for Energy.

The PACS virtualisation must be the objective. However, a series of stages need must be gone through before setting on the “right route” to virtualisation. The performance of the most critical protection and automation functions must be validated once they have been virtualised. It is also vital to validate the interoperability framework established for the **R#SPACE** project (which will be done in the project’s system integration phase). The economics and profitability of a virtualised solution must also be confirmed. Lastly, it is necessary to plan the industrial development needed for such a solution.

4. The synchrocheck recloser function is designed to connect two separate asynchronous networks by closing the circuit breaker at the appropriate moment if conditions allow.



## FROM "HARDWIRED" TO "DIGITAL" CONTROL SYSTEMS



### Further reading

- IEC 61850 Demystified, H. Falk - Artech House Publishers (2018)

# INTEROPERABILITY: SOLUTIONS AND CHALLENGES



**Volker LEITLOFF** | Distinguished Expert, Local  
Automation and Control  
Bay Protections and Functions

**The digitalisation of interfaces, the possibility of greater interoperability between the equipment from different suppliers, and functional upgrades, provide new opportunities PACS. The R#SPACE project makes the most of these opportunities. In addition, with its “Postes Intelligents” project, RTE benefits from considerable proven operating experience, which the company can exploit and communicate to the standardisation bodies and other transmission system operators.**

PACS have benefited from technological advances that have made them more compact and less expensive. These improvements have sometimes been achieved at the expense of greater complexity and various maintenance constraints.

With the current performance of processors, all types of functions can be implemented on the same physical platform. The latest generation of IED is therefore potentially a modular multi-function IED that can simultaneously host and operate several protection and control functions, depending on its physical composition and its configuration. A logical extension of this functional integration is the partial or full virtualisation of these functions in servers.

At the same time, the interface between protection equipment and control equipment has evolved. Although the first digital IEDs were almost entirely hardwired, substation communication buses appeared. These were often proprietary buses that provided an interface between the bays and the substation.

The digital interfacing of the process is a recent

development, driven by the wide application of the IEC 61850 standard. It is this digital interface that constitutes the “process bus” and replaces the hardwiring of HV equipment (instrument transformers, breakers, disconnector switches) to protection and control IEDs. This development allows the geographical separation of these equipment and the IEDs hosting the protection and control functions. The absence of any requirement for physical proximity introduces flexibility for architecture of PACS. This development is leading to the creation of a new digital “process” interface, which will first be implanted between the “traditional” hardwired interface and the fully digital PACS. It is made up of interface IED<sup>5</sup>.

It is worth noting that subsequently, thanks to the standardised IEC 61850 “process bus”, it is possible to modify or replace the digital instrumentation and control system while keeping the installed interface equipment. The latter can also be replaced whatever the type of the fully digital PACS.

It therefore becomes possible to separate the purchase and the replacement policy of digital interface equipment from those for PACS, thereby

5. Communication network used for the “process” interface.

6. Devices that include switchgear control units (SCU) for logic interfaces, and merging units (MU) and stand-alone merging units (SAMU) for analogue interfaces.

delivering considerable flexibility and room for manoeuvre. Smart primary equipment can also be introduced, that is to say, HV equipment with an integrated IEC 61850 interface, such as a low-power instrument transformer (LPIT).

Furthermore, there are potential synergies between a PACS interface of HV equipment and its monitoring. These two functions partly rely on the same data and can share the same infrastructure to transmit measurements and data to the substation and beyond.

The introduction of a digital “process” interface will alter the boundary between the instrumentation and control system and the process, paving the way for new opportunities and possibilities.

obtain true interoperability between two functions, it is therefore necessary to define the syntax and to specify these configurations and implementations. This covers several aspects: a common data model, the compatibility of the function profiles, and the specification of IEC 61850 name spaces and services that are to be made available by the equipment hosting the functions.

Finally, the 3<sup>rd</sup> level of requirements relates to functional interoperability. There must be consistency between the behaviours of the different functions of the PACS, even in degraded conditions. This aspect is covered by the “traditional” PACS specifications. Whenever possible, the specifications can be based on functional standards, such as those of the protection functions.

### Interoperability

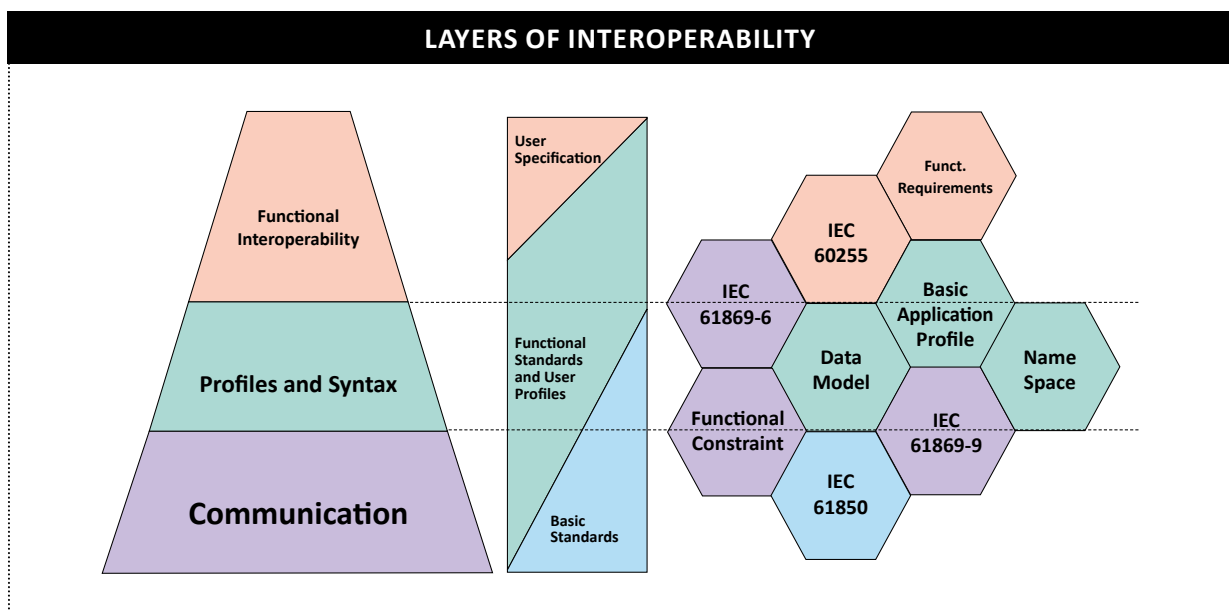
The “Postes Intelligents” project has clearly highlighted that “mere” IEC 61850 compatibility between different equipment and functions is not enough to guarantee full functional interoperability. Other requirements must be met.

3 main levels of requirements can be identified (see illustration). The “communication” level corresponds primarily, for the PACS functions, to an IEC 61850 compliant implementation. For the “profiles and syntaxes” layer, IEC 61850 gives a lot of flexibility in the choice of implementation, of configurations, but also of interpretation of objects and data. In order to

### Functional developments

Many protection or control functions have evolved from one equipment technological stage to another, and new functions have been added. The digitalisation of PACS fosters these advances. Furthermore, other functions are now possible or are simpler to execute.

Constraints associated with changes to the network (introduction of renewable energies, operation of installations closer to margins) require the development and deployment of specific protection or control functions that are often unavailable in of the shelf bay equipment. With access to bay data, digitalisation allows these functions to be hosted



in specific substation equipment. This means that they can be developed and overseen by RTE. Several substation functions are involved, particularly overload controllers, voltage regulation controllers, topological management and associated functions, and supervision functions such as the verification of consistency in the electrical quantities measured.

Protection schemes<sup>7</sup> define the protection functions to be implemented for a given installation or type of installation, and set out the corresponding redundancy and reliability requirements. Therefore, they are not intended in principle to evolve with a change in technology. However, in the past, the options provided by a new technological stage may have led to their upgrading. Conversely, a desirable protection function is not always prescribed, owing to technological limitations and/or implementation costs.

The protection functions that will be easier to implement in an fully digital PACS include busbar differential protection<sup>8</sup> and differential protections for other HV equipment in the substation. The introduction of the “process bus” means that in principle it will “only” be necessary to connect the smart equipment implementing the function to the existing interbay “process bus” in order to deploy these differential protections.

Furthermore, upgrades in protection functions and/or protection schemes may be needed in the near future to factor in various constraints, such as the onset of network zones with converter connected generation, characterised by a very low short-circuit current and other features. Some of these functions are potentially easier to develop and implement in a fully digital PACS model. Functions using travelling waves<sup>9</sup> (TW) are a notable exception, as the process bus and acquisition equipment that are currently available are not designed for the sampling frequency required by these applications.

In any case, the protection schemes or new protection functions must be defined and designed with reference to advances in the network and in primary equipment.

## Opportunities and challenges

Other transmission system operators (TSO) have built and commissioned fully digital PACS demonstrators with varying characteristics, most notably Scottish Power (UK, FITNESS), Transgrid AU (AU, Avon) and Statnett (NO, Furuset). The majority of the leading suppliers of PACS have participated in the work carried out by one or more of these demonstrators. They make the largest contribution to the standardisation bodies. The representatives of suppliers of test systems have also been actively involved. In contrast, few TSOs, have generally been present in the standardisation bodies.

There is a more balanced participation in the CIGRÉ working groups and, for some years now, an informal exchange group for TSOs has been meeting on the fringes of CIGRÉ sessions. There have also been several bilateral contacts between RTE and European TSOs on this subject.

In the course of the competitive dialogue tender procedure for some of the **R#SPACE** project batches, suppliers occasionally expressed hesitation in committing their development resources to RTE specifications that may subsequently prove to be different from, or incompatible with, future standards and guidelines. It is therefore important to make a special effort on the most sensitive topics during the work of the standardisation bodies, if possible in conjunction with the suppliers who have performed these developments, and with other TSOs.

Exchanges and coordination with other TSOs are also essential in order to have common guidelines for their specifications. Carrying over some key themes from the **R#SPACE** project to WG 10 TC 57 and to TC 95 will underpin the specifications by building them into the standards. This may also provide momentum for the broader deployment of “process bus” PACS which can be interfaced with LPIT of , with economic benefits for all parties.

The functional integration made possible by advances in digital technology should lead to the increasing virtualisation of instrumentation and control functions. A first stage in this virtualisation will be deployed as part of the **R#SPACE** project and will initially involve almost all the substation functions.

7. It should be pointed out that a distinction is to be made between a protection scheme and a technological stage of PACS. The protection scheme defines the protection functions that are implemented. Thus, a protection scheme can be altered without changing the technological stage of the PACS, and vice versa.

8. Busbar differential protection: a protection function to detect busbar faults by monitoring total incoming current, which must be zero in normal operating conditions.

9. Electromagnetic waves generated for example at the location of an insulation fault.



All the specification and standardisation work carried out to reach functional interoperability will not be invalidated or rendered superfluous by the functional integration and the virtualisation of PACS. The interoperability of virtualised functions will be based on the same principles as those

developed for digitalisation, and will draw on the same standards, guidelines and specifications. In any event, the development or upgrading of protection functions will continue to be aided by the digitalisation of PACS.



### Further reading

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- **Basic Application Profiles**, M. Merley, C. Bloch - PAC World Magazine (juin 2021)

# TOWARDS ENVIRONMENTALLY FRIENDLY AND DIGITAL SUBSTATIONS

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**Pascale PRIEUR** |

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The energy transition is not the only crucial factor for the design of innovative substations. As well as overhead lines and underground cables, high-voltage switchgear and controlgear are an integral part of an electrical power transmission system ensuring a recognized quality of service and supply security. Therefore it is necessary to adopt a holistic approach: we must ensure that the design of this equipment fits into the existing system, while considering its contribution to the transformation of the network. The knowledge alone of how this network operates is not enough, as the components, be it the substations or the wiring and cabling, all interact.

Switchgear and controlgear consists of electrical equipment or assemblies designed to establish and/or interrupt an electrical current. This scope includes circuit breakers, disconnectors, earthing switches, and assemblies (gas metal-enclosed switchgear, compact substations). That does not however cover all substation equipment such as power transformers or compensation equipment (winding, battery, filters).

The scale of the changes to the electricity system required by the energy transition equals that of the transformations that followed the development of nuclear energy after the second oil crisis. When the French fleet of nuclear power plants was developed, the adoption of 400 kV voltage had a lasting impact on the network. From 1978 to 1987, no less than 8,000 km of 400 kV power lines were constructed, and the 225 kV network was gradually replaced by the 400 kV system as the backbone of the power transmission network.

This marked a culmination of land use and industrial logistics strategies pursued since 1946 under the aegis of the national operator EDF. In the context of a 6 to 7% annual rise in energy use, the nationalisation of a number of electricity companies enabled the standardisation of frequency and voltage levels. The issue of voltage levels has been addressed from the outset with a view to a European transmission network.

Since 1946, the development of the transmission network has responded to strategic issues that

can be summarised as follows: act on the means of generating electricity in order to boost national economic growth and strive for energy independence, ensure that the network is connected internationally and, lastly, seek best value for money. These challenges are still alive and well but within a changing environment.

### Combining development and replacement

The ongoing reshaping of the transmission system, the driving force of disruptive innovation in the design of substations, is linked to the determination of the economic optimum but also to the significant developments in electricity production and use. The sources of transformation will certainly stem from the connection of renewable energies, particularly offshore platforms, but also from the technologies selected for electricity links, with a marked increase in the number and length of underground cable systems, and even submarine cable systems, some of which will be direct current links.

## STANDARDS, ESSENTIAL REFERENCE BASELINES AND OPPORTUNITIES

Standardisation provides a reference framework that sets guidelines and technical or quality specifications for products. It benefits from a collective know-how and thus *“fosters the development of the industry. It also fosters innovation, as it puts forward reliable methodologies and data<sup>1</sup>.”*

For RTE, the challenge is to ensure that the standards remain consistent with the transformations that have been or will be implemented. Due care must be taken that the network transformations do not warrant modifications to ratings and requirements. It is also necessary to monitor the introduction of digital technology in switchgear and controlgear.

Stakeholders agree on the timeliness of the introduction of digital technology, and are taking positive action. In 2006, for example, an IEC 61850 compliant standard for digital interfaces in HV switchgear and controlgear was created (and revised in 2015). Another focal point for stakeholders: the challenges associated with the environmental footprint reduction targets.

1. According to AFNOR (French National Organisation for Standardisation) and BNQ (Quebec Standards Development Office)

Looking ahead, network performance will have to balance development with replacement. What is new is the focus on asset management to the detriment of network development. An order of priority that will prevail in light of ageing equipment and large equipment replacement forecasts.

For many years, sustainable development underpinned investment in the transmission system. In the past, this entailed controlling the landscape footprint, a decisive factor for public acceptance. This time, the European Commission's injunctions to apply environmental impact assessment methodologies will affect the way the European power systems operates and consequently the design of equipment.

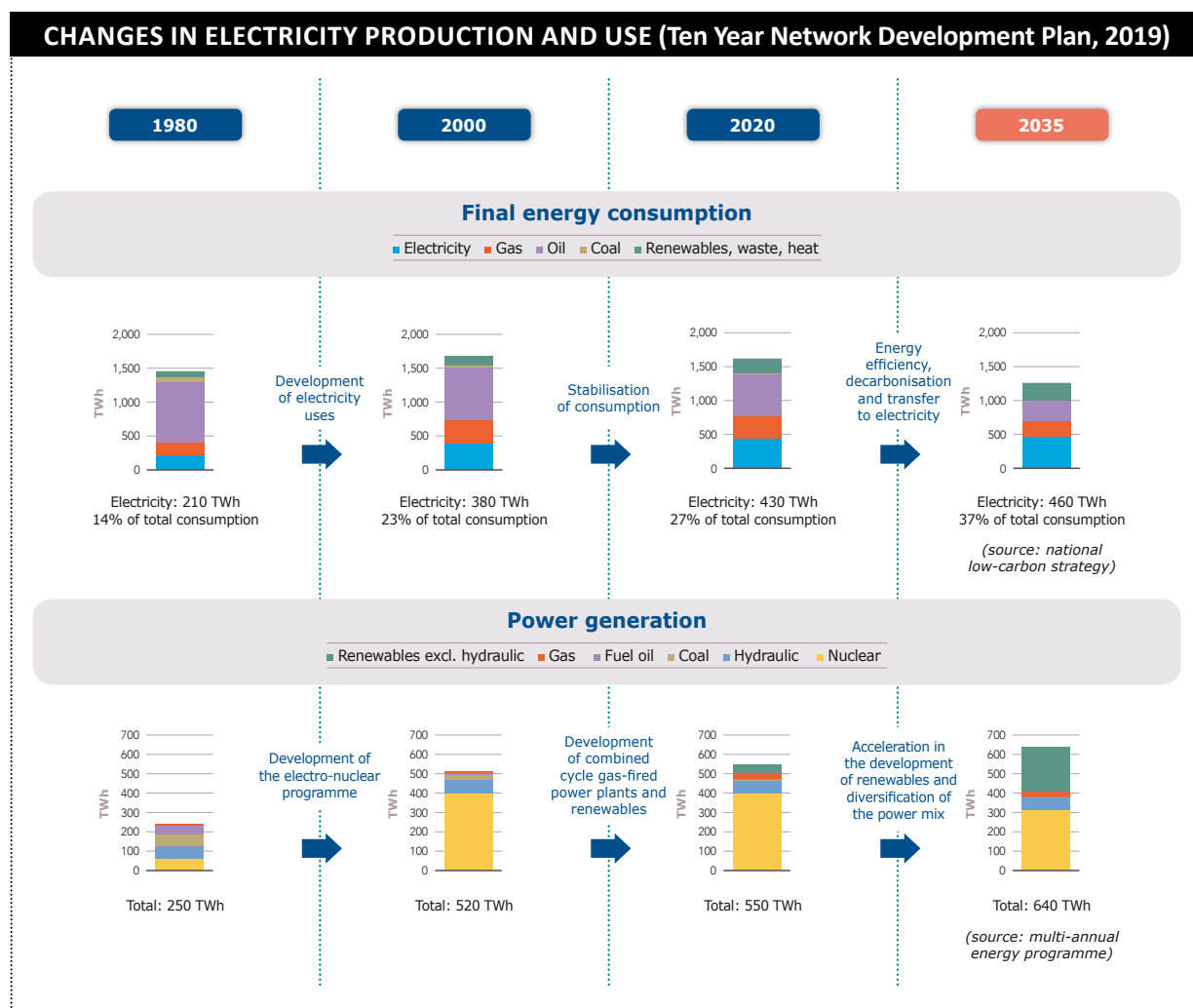
### The challenging optimum economic assessment

Lastly, another vector of change touches on the expectations, and those of the regulator in particular, for acceleration of the network transformation process. Expectations that impacts on the timeframe for the economic optimum assessment.

RTE is constantly looking for the economic optimum. In its analysis of the 2019 Ten-Year Network Development Plan (SDDR), the Energy Regulatory Committee (CRÉ) urges going one step further by evaluating the efficiency of the policies already implemented. This scrutinises the assessment of services provided by the network (performance of system components) in light of regulator and customer expectations, as well as constraints.

The main challenges in finding this optimum are the balance between the different time scales (service life) and geographical considerations (within the network), and the creation of a transversal organisation in terms of human (skills, expertise) and equipment resources (interoperability).

Like other components of the transmission system, the challenge for switchgear and controlgear is to implement new technological solutions that give the electricity system ostensibly contradictory properties: complexity and resilience, flexibility, and durability.





## Looking beyond purely technical performance

The roadmaps of manufacturers and transmission system operators are in agreement on the major transformations of electricity networks. Firstly, there is the hybridisation of the network with the penetration of HVDC technologies, particularly for interconnections, and owing to offshore platform connections. Then come the challenges of digital technology in regard to asset management and power system flexibilities. Finally, there are the commitments to carbon neutrality by 2050, spearheaded by the alternatives to SF<sub>6</sub>.

These transformations will not give rise to technological breakthroughs in substation switchgear and controlgear, aside from HVDC equipment. However, they will lead to upheavals with the interfaces between high voltage equipment and instrumentation and control systems, as well as more interactivity between the network's operation, development and asset management.

The development of the electricity system must ensure a balance between generation and consumption, guarantee flows, and pre-empt the consequences of off-normal events and incidents. The choice of each component therefore meets the requirement of, and constraints imposed by the system. In turn, equipment affects the level of the constraints to which it is subject, and the operation of the system that it is part of.

High-voltage equipment continues the rationalization implemented for the network development by applying it to the ratings. For switchgear and controlgear, these ratings are the subject of a separate chapter in the standards<sup>2</sup> and by extension in RTE's specifications. They are certified through compliance testing and can be summed up, excluding the auxiliaries, as:

- Rated voltage  $U_r$
- Rated insulated level ( $U_r$ ,  $U_d$ ,  $U_p$ )
- Rated frequency  $f_r$
- Rated continuous current  $I_r$
- Ratings of short-circuit current (rated short-time withstand current  $I_k$  ; rated peak withstand current  $I_p$  ; rated duration of short-circuit  $t_k$ )

These ratings also apply to other substation equipment.

### Evolving and embracing external constraints

The ratings, design and construction do not fully set out the need and use of high voltage equipment. A functional approach allows a more detailed description of requirements and uses, thus paying due attention to other performances and constraints.

Since 2010, the technical solutions set in motion to support flows, while controlling the landscape footprint, have become more diverse: energy compensation mechanisms, long-distance underground cable systems, etc. They have been accompanied by measures designed to guarantee the operating safety of the electricity system (upholding the voltage plan, high-voltage issues) and quality of service (harmonic filtration). This is coupled with the development of infrastructures for the connection to offshore platforms and substations. It is reasonable to assume that these network transformations will give rise to major changes to the ratings of switchgear and controlgear.

The lifecycle of equipment also enters the equation. Regarding SF<sub>6</sub>, there are alternatives for gas insulated switchgear and for air insulated circuit-breakers (see box). The use of SF<sub>6</sub> in all remaining electrical equipment supplied by RTE will be suspended pending a review of procurement contracts<sup>3</sup>. In addition to technical performance, these alternative solutions, and more generally the equipment itself, must meet health and safety requirements of staff and the public. They must also meet environmental requirements<sup>4</sup> and regulatory obligations.

These solutions must also meet expectations for service life, in alignment with the depreciation periods of industrial products. Lastly, they must satisfy market mechanisms, and RTE must ensure that the market has the capacity to sustainably meet its development and replacement needs.

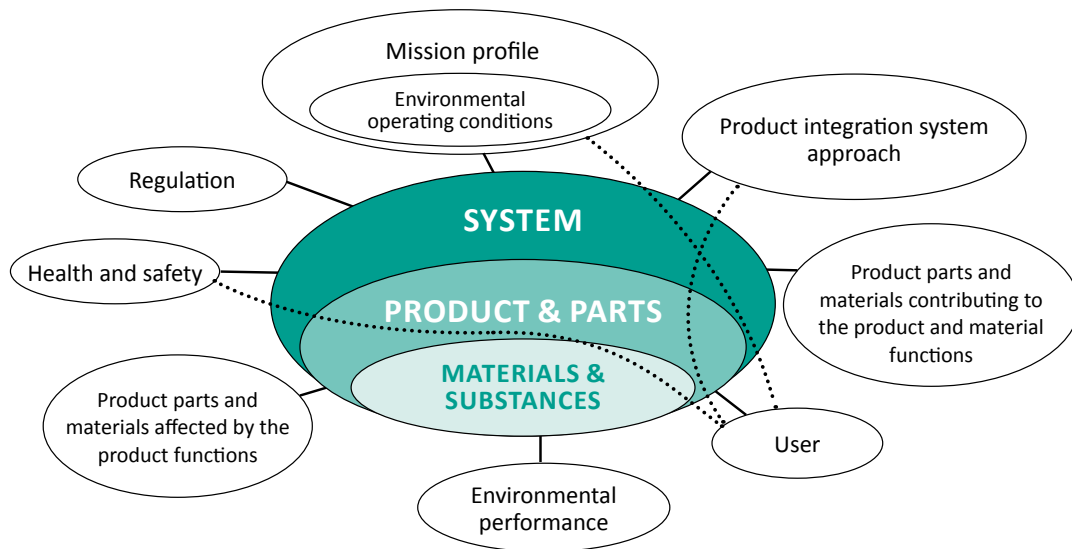
The ramping up of transmission system transformations leaves little time for building consensus. For innovation to go hand-in-hand with industrial deployment, the equipment development process must transcend the differences between stakeholders. It must also rethink the interfaces between equipment

2. Circuit breakers, current disconnectors, metal-enclosed substations are all covered by the IEC 62271 series

3. This applies already to a very small proportion of the total installed mass (SF<sub>6</sub> terminals of underground cables, bushings of power transformers)

4. RTE has set out three priority impact areas: climate, biodiversity, raw materials

## FUNCTIONAL ANALYSIS FOR A SYSTEM, PRODUCT, PART, OR MATERIAL



(Source: Thierry Cormenier and Martial Patra, *How standardization for Ecodesign and Circular Economy contributes to sustainability*)

by setting out assessment methodologies and tools, based on a functional analysis of equipment factoring in systemic considerations (network and its components, cabling and wiring, substations, equipment) and timescale. To this end, roadmaps drafted by manufacturers and users, spanning development and implementation, must be shared, with pooled pilot trials by transmission system operators.

### The introduction of digital technology

The introduction of digital technology serves two purposes: to replace existing functions, particularly in relation to monitoring and control (by means of distributed intelligence systems), and to provide new services, notably for asset management.

The development of low power instrument transformers (LPIT) contributes to the first goal. RTE has invested in several trials with the manufacturer Alstom Grid, and has more recently worked with Siemens on an LPIT development project for metal-enclosed switchgear (substation at Novion). To date, trial schemes have not led to the roll-out of new products.

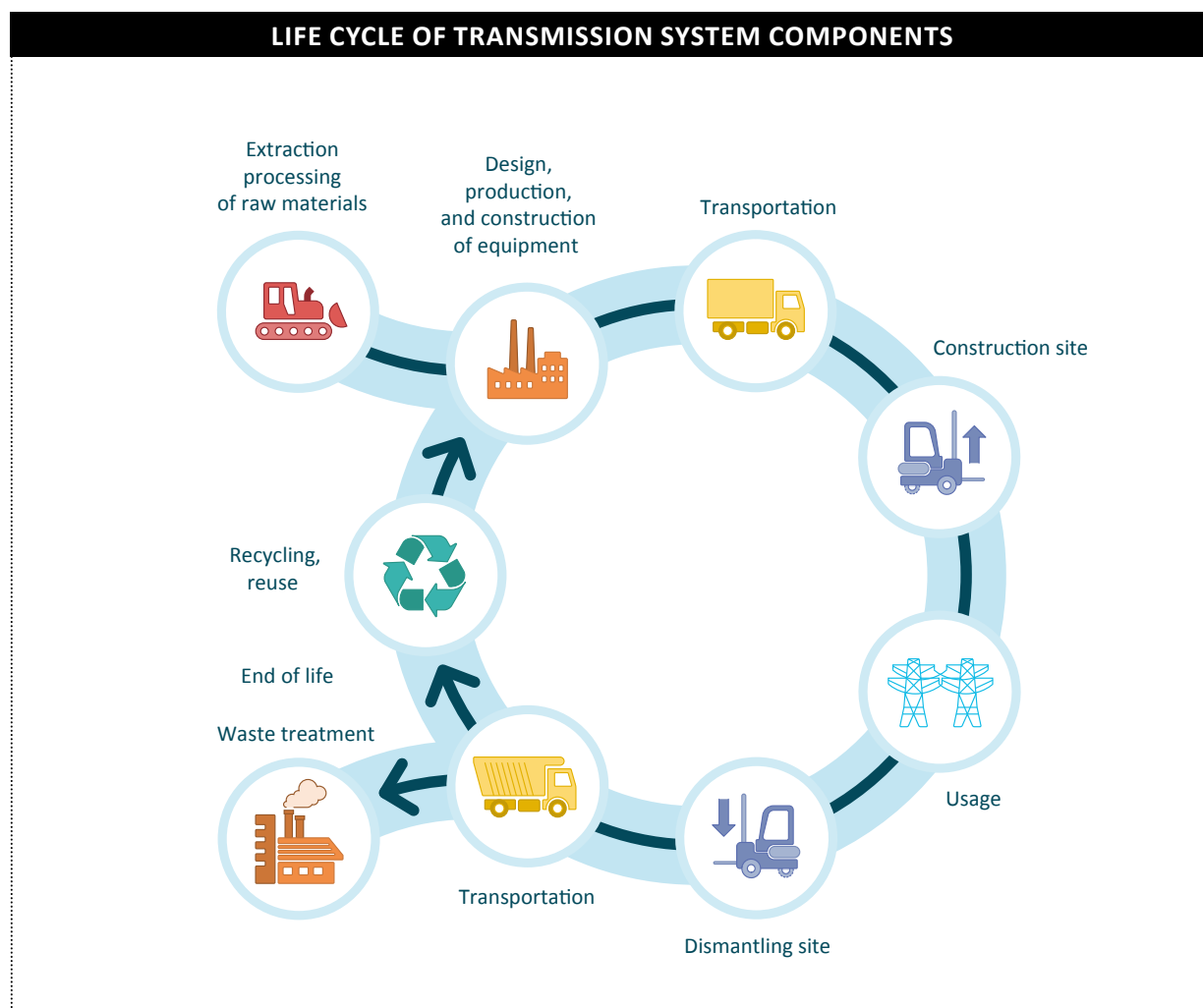
## ALTERNATIVES TO SF<sub>6</sub>

The search for alternatives to SF<sub>6</sub> is intended to contribute to the carbon neutrality objectives set by the European Commission and the French government<sup>5</sup>. SF<sub>6</sub> emissions are the 3<sup>rd</sup> source of greenhouse gases after electricity losses and assets in RTE's inventory. The equipment concerned comprises gas insulated substation and circuit breakers.

RTE is committed to reducing SF<sub>6</sub> emissions into the atmosphere. Given the environmental issues, an eco-design process is required, covering lifecycle thinking, integration into existing systems, and taking into account the service conditions. A process that aims to balance the constraints associated with each one of RTE's activities (development and engineering, maintenance, operation, procurement, etc.).

In coordination with its European counterparts, the company is developing a timetable for the introduction of alternative technologies.

5. The French National Low-Carbon Strategy (SNBC) is one of the policy areas of the Climate-Air-Energy Plan, which is the country's roadmap for preventing, and adapting to, climate change



Furthermore, there are prerequisites for the roll-out of such solutions to guarantee modularity and interoperability. These solutions disrupt the interfaces between HV equipment and instrumentation and control systems. They call for a non-proprietary communication protocol (IEC 61850) and the standardisation of the digital interfaces of HV equipment. By way of illustration, it has taken more than 15 years to fulfil these preconditions.

On the strength of these advances, manufacturers and users have set themselves a new challenge: the digital twin (see box). The technological hurdle to overcome is no longer communication but a shared data model.

#### **Outlining tomorrow's electricity system, resilient and resource-efficient**

The increasing pace of transformation may well

shake up the network development models of today and usher in not yet manageable complexity. To prevent these risks, ontologies (see box) and the circular economy offer opportunities, as they enhance a comprehensive overview of the system and support transversality between trades.

Consideration of the circular economy has prompted RTE to take a fresh look at the services provided by high voltage equipment, and thus review asset management policies. To do so technical performance should be added performance as regards the environmental impacts on the life cycle of electrical equipment (see illustration). Reliability alone does not provide an adequate description of equipment behaviour. The requirements of specifications should be extended to maintainability and durability. The consequences of the failure of a piece of equipment should be considered at the scale of the electricity system, in order to define service continuity arrangements that are adapted

## ONTOLOGIES AND DIGITAL TWINS

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Ontologies create an opportunity to streamline the exchanges between experts and stakeholders, by modelling the knowledge associated with the concepts and data used by all. They offer a shared understanding of the functioning of the electricity system and its components. Ontology is, in fact, a bridge or a translator for qualified personnel dealing with the same property, possibly named differently, and with a different purpose.

The goal of the digital twin is to support asset management decisions about equipment by using the data and knowledge accumulated over the life of the equipment. In order to reach an overall optimum, the data and knowledge must be accessible to and shared by all, whatever the intended uses.

For RTE, the challenge is to offer each stakeholder in the asset's life cycle a comprehensive overview of its service conditions, expected services, and behaviour. This is a long-term endeavour, and the difficulties are analogous to those encountered during the introduction of digital technology in substations, concerning the communication protocol.

to the importance of the equipment, and to specify them accordingly. This would help address the vulnerability of the equipment, and of the electricity system more generally, in respect of exceptional events linked to climate change.

In the absence of any technological breakthroughs for switchgear and controlgear, assessing the electricity system and its components from this fresh perspective, in light of lessons learned from the past, is not time wasted but rather an assurance of a resilient and energy-efficient network.



### Further reading

- **Évolutions du réseau de transport d'électricité – vecteur du développement durable (Changes to the electricity transmission network- a driver of sustainable development)**, led by A. Croguennoc and B. Dalle - Édition Lavoisier (2011)
- **ENTSO-E - Research, Development & Innovation Roadmap 2020-2030**, ENTSO-E - available at <https://www.entsoe.eu>
- **How standardization for Ecodesign and Circular Economy contributes to sustainability**, T. Cormenier, M. Patra - Livre blanc Schneider Electric (2020)
- **Penser global (Think global)**, E. Morin - Flammarion (paperback edition, 2021)



# LIVE WORKING, A LONGSTANDING BUT OFTEN OVERLOOKED TECHNIQUE

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**Sophie CHABIN**

Distinguished Expert,  
Live Working

Live working is a method for optimised maintenance of the electricity system, but it is also a driver of excellence for the safety of RTE employees and the development of their skills. It is fully aligned with the company's business plan.

Although live working has been in use for over 50 years, it is largely overlooked except in maintenance operations, and in view of the challenges facing RTE, it deserves a new impetus.

**In France, live working (LW) is defined in standard NF C 18-510. The standard sets out that live working is an electrical operation during which an operator comes into contact with exposed live parts at low or high voltage and/or enters a live high-voltage work area, either with parts of his body or with tools, devices, conductive material, or equipment.**

**The technical know-how for LW concentrated in a centre of expertise: SERECT.**

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For France, the story of live working started at the end of the 1950s with fact-finding missions around the world to learn from the experience of other countries. Building on this information, EDF started using LW in 1960. At the time, EDF deployed this technique for economic and social reasons. In a society where electrical power was increasingly ubiquitous, disconnecting customers to carry out work was no longer an option. Network workers had to intervene outside of working hours to minimise disruption, and often worked under time pressure, which led to accidents. LW presented a solution to these problems. And if we take a closer look, we can see that history is repeating itself...

The current constraints on the electricity system are different but we can draw parallels between 1960 and today: RTE's customers are highly sensitive to the quality of electricity supply and cannot do without power, be it LV or VHV.

In regard to the rules for electrical work, regulations in France make a clear distinction between installations and facilities. Thus, the term "installation" is used exclusively for electricity transmission and distribution systems, and their auxiliary systems (whoever the operator). The term "facilities" covers everything that does not meet the definition of an installation.

Labour legislation does not apply to electrical work carried out in installations and auxiliary systems. This is governed instead by decree 82-167, which allows RTE to choose how it conducts electrical work (live or dead) with no requirement to justify the decision. This is of crucial importance, not just for RTE, but also for Enedis. It allows the "straightforward" use of the LW method according to the needs of each company. However, the situations in which LW may be used are specified in each company's LW policy.

Decree 82-167 also designates the Live Working Committee as the body responsible for setting the rules (see box). Although favourable to the use of

LW in installations, the regulations come under a decree that is not codified in labour legislation, leaving them weaker. In addition, in the past, the ministry responsible for energy was also the competent ministry for work on installations, which is now the remit of the Ministry of Labour. The latter is unfamiliar with LW and somewhat wary.

## **A DEDICATED NATIONAL BODY FOR LW**

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The Live Working Committee sets the rules and defines all the regulations for live working in electrical installations. It approves the methods of work, and the technical datasheets for the safety equipment specifically intended for LW. It is also tasked with endorsing training programmes and certifying training centres.

The LW Committee draws on the expertise in SERECT to perform these tasks.

The 18-member Committee includes representatives from the Ministries of Industry and Labour, the transmission system operators using the LW method, subject-matter specialists in the fields of risk prevention, training and research, as well as the coordinators and secretaries of regulations review committees (one committee per voltage range).

# Management, control of risks and R&D

Live working requires full control at all times, whatever the method of work, of the risks of short-circuit and electrification in the different circuits: phase-to-ground and phase-to-phase. In order to manage these two risks, it is vital to always control the distance between the parts and/or the operator at different voltages, to control overvoltage that may spread across the work area, to control the conductivity of the tools, and to control the environment of the operators.

Furthermore, during live working, operators are required to connect and disconnect conductive parts or themselves. The connection or disconnection of a conductive part generates an arc by interrupting or forming a capacitive current. To ensure the safety of the operators, measures must be taken to control the arc's voltage, length, and trajectory.

Lastly, it is essential to control the electrical features and mechanical characteristics of the LW tools. Insulated tools fall into two categories: they provide either longitudinal insulation (tube, rope, wire) or transverse insulation (blanket, gloves, mat, protective cover).

Since the beginnings of LW, the basic component of longitudinal insulation has been the insulating tube, made up of fibreglass embedded in an epoxy resin matrix. The inside of the tube contains waterproof polyurethane foam to prevent any penetration and build-up of moisture. It must have the same dielectric properties as an air gap of the same length.

In addition to their dielectric requirements, the tools must also have the appropriate mechanical strength for their use. Depending on their intended use, a trade-off must be made between their dielectric behaviour and mechanical strength. Materials with the required electrical properties do not have the right mechanical properties, and vice versa.

## LW and safety: a contradiction in terms?

At first glance, working on live electrical systems and working safely are two concepts that appear contradictory. However, in practice, they are not. The LW method has been developed to increase the safety of operators. Working on live systems does away with time constraints; for the electricity system, operations are clear-cut, and tasks can be carried out in a calm and unhurried manner. Moreover,

live working means being alert to the voltage and being mindful of the danger.

The risks are managed at multiple levels: from the tools used and the operators, to the tasks and the employers. The LW rules and tools are specified and designed in accordance with electrical constraints. The operators receive specialist training and regular refresher training based on established training programmes. For work execution, each task is prepared in advance, and an operating procedure is written for each operation, setting out the stages and tools to be used, adapted to the specificity of each task. The work supervisor is the conductor of the orchestra in the field, and the operators are under his orders. Finally, the employer follows the work of the operators to guarantee that professional standards are upheld throughout.

Industrial safety results show that LW causes fewer electrical accidents than dead working. There is still an electrical risk during work on a de-energised system, even if the risk may appear to have been “eliminated”. There are risks when implementing and removing lockouts: incorrect identification of the installation requiring lockout or lockout removal, incorrect earthing and shorting practices, noncompliance with the safety distance from energised installations, and even risks due to induction.

## An R&D programme overseen by SERECT

In regard to R&D, SERECT's expertise was based historically on the skills and testing methods of EDF R&D. The work was focused primarily on the electrical phenomena accompanying LW: behaviour of the air gap, connection/disconnection phenomena, dielectric behaviours of materials, etc.

After the discontinuation of all work with EDF R&D<sup>1</sup>, European laboratories and universities were surveyed to determine their know-how in these areas. But few organisations have both the skills and means for testing, and the associated expertise. Therefore, the organisation of R&D studies for LW had to be thought out afresh. SERECT rebuilt an R&D programme for 2020-2023. The programme is divided into two technical areas of focus: “inspection of tools and equipment” and “new tools and improvements to existing tools”.

<sup>1</sup> The Third Energy Package prohibits RTE from entering into trade agreements with EDF, such as sub-contracting studies or tests.

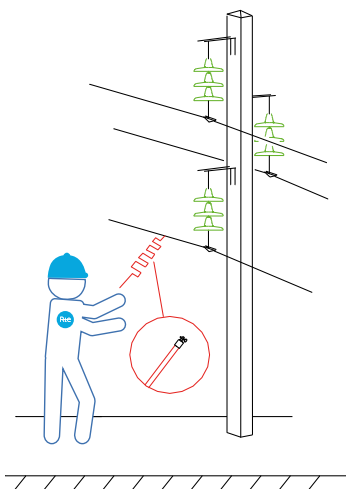
The focus area of “inspection of tools and equipment” must deliver new methods for inspecting the LW tools in use. It must also identify techniques for inspecting composite insulator chains and columns that allow for work to be carried out on or near this network equipment.

The focus area of “new tools and improvements to existing tools” seeks to update the tools and methods used in LW operations. It aims to identify alternatives to existing tools, bring in new technologies to develop innovative tools like robots or articulated arms, redesign the connection-disconnection devices, improve workstation ergonomics, and control overvoltage.

Since its creation, SERECT has run a testing and research laboratory. Its testing resources and expertise now allow the laboratory to carry out electrical tests at industrial frequency, in dry conditions or in simulated rain, at up to 300 kV. This laboratory is accredited by COFRAC<sup>2</sup> for dielectric behaviour tests before and after humidity conditioning, and dielectric behaviour testing under rain conditions.

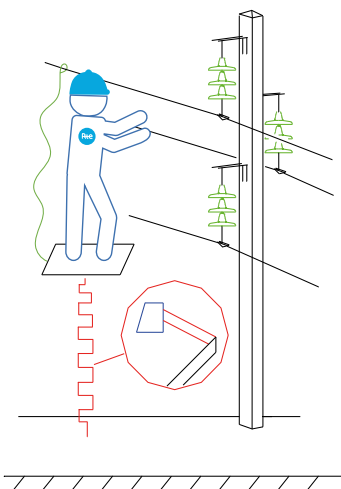
### THE 3 METHODS OF LIVE WORKING

#### THE HOT STICK WORKING METHOD



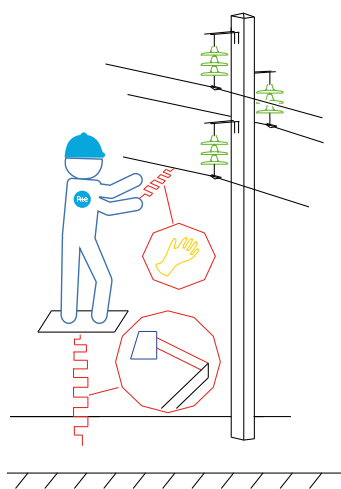
The operator remains at earth potential. He works using tools that are attached to the ends of insulating poles. This method can be used for all voltage ranges. Workstation ergonomics are limited, particularly for high voltage systems that entail working at a considerable distance.

#### THE BARE-HAND WORKING METHOD



The operator, insulated from earth, is brought to the potential of the component he is working on. Depending on the type of operation, he is protected by way of the insulated boom of an elevated work platform, or an air gap. He must maintain at all times a minimum working distance from all the components in his environment that are at a different potential from the one he is working on. This ergonomic working method is implemented for HV and MV ranges.

#### THE INSULATING GLOVE WORKING METHOD



The operator is protected depending on the potential of the parts he is working on. He wears insulating gloves and keeps at a minimum distance from all the components in his environment at a different potential from the one he is working on. With HV systems, he is standing on an elevated work platform with an insulated boom. Deployed for LV and HV ranges, this method is more ergonomic than hot stick working.

<sup>2</sup>. In accordance with standard NF EN ISO IEC 17025 of 2017.



## SERECT, RECOGNISED EXPERTISE AND A REGULATORY ROLE

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Established in 1962, The Design, Execution and Testing Section of the Technical Committee (SERECT) was tasked with developing methods and tools for live working on behalf of EDF. SERECT provided support to the Technical Committee (today's LW Committee), which oversaw the deployment of this technique in France.

In 2009, after ERDF became a subsidiary, the question of SERECT's integration arose. EDF ultimately relinquished SERECT to RTE but all parties agreed that SERECT should continue to concentrate its expertise on the three voltage ranges, and should draw up contracts in particular with ERDF (Enedis). Within this framework, it assists Enedis with live working.

Today, SERECT is a department of CNER (National Centre for Network Expertise). Its responsibilities include:

- assistance to the LW Committee
- the development of live working equipment
- technical support
- the provision of standard-compliant tools
- the coordination of LW at RTE
- training on periodic inspections
- technical support for RTE subsidiaries
- technical monitoring.

SERECT has kept its distinctive “rule-setting” or “regulatory” role<sup>3</sup> for all LW stakeholders working on installations. It is a unique centre of LW expertise, acting on behalf of the LW Committee and all parties concerned by the decree of 1982. Among other things, SERECT can carry out experimental work, or have it carried out, for the development of new methods.

For many years, French expertise and the expertise of SERECT more specifically has been widely recognised at an international level (box on the different LW strategies). This know-how has been put to work by EDF since the end of the 1990s, with several projects leading to the deployment of the French LW method in other countries.

## ○ A chain of expertise: from SERECT to field operators

Although operatives were keen to take up live working in the 1980s and 1990s, this is no longer the case. There is little awareness of LW, and it is important to tap into this activity. It is vital to maintain a minimum level of trained professionals. For the VHV range, the operatives with T<sup>4</sup> qualifications are all RTE employees. At the end of 2019, they totalled 272 and had performed approximately 112,000 hours of LW operations. These figures were lower than in previous years. The peak in activity dates back to 2013, with 161,000 hours of work by a total of 284

operators. The start of 2020 was severely impacted by the Covid crisis, and activity has remained low despite the efforts of the teams and their managers since the end of lockdown.

Several operations were cancelled in 2019 owing to resource issues (one person on sick leave can lead to the cancellation of an entire operation), due to the reprioritisation of team assignments in response to hazards or damage or - and this is a new development - because of issues linked with

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3. In accordance with decree 82-167 of 1 February 1982 and with the inter-ministerial decision of 1 July 1983.

4. Qualification authorising live working.

placing the installation on which LW is due to take place under a special operating regime. Too sharp a reduction in the number of operators may make it increasingly difficult to schedule work.

Furthermore, as a consequence of significant turnover and retirement of LW-qualified employees in recent years, the age profile of the teams is considerably younger, particularly among work supervisors. A key issue is preserving know-how across the entire chain of expertise, from SERECT to the technical supervisors of LW teams (especially for complex operations). The challenge is to continue to foster supervision on the front line, not only to check the work that is carried out (at the preparation stage and in the field) but also to build confidence, enhance skills and provide support.

### **Quantitative and qualitative criteria**

Through its LW policy, RTE ensures that its operators demonstrate the highest level of professionalism. Aside from overseeing their specialist skills with the backing of SERECT, the company also sets itself requirements that factor in not just quantitative criteria (a minimum number of hours worked by each employee) but also a qualitative standard. For VHV LW, this qualitative standard must be met at various levels: employee, team, maintenance centre, and corporate level.

Live working on installations is a maintenance technique that is essential to successfully meet the challenges facing transmission and distribution system operators, particularly in light of the energy transition. Building on the efforts already made, continued vigilance is needed in monitoring changes to the standards that govern both equipment and electrical work. It will also be necessary to continue adapting both the tools and the rules not just to network developments but also to societal constraints (the need to improve ergonomics, to modernise techniques, and to mechanise operations).

## **A WORLD SPLIT BETWEEN DIFFERENT LW METHODS**

In France, given the variety of network equipment, from the 1970s onwards SERECT began developing a LW method based on two main aspects. First, a corpus of rules referred to as the Working Conditions (CET) and, secondly, a corpus listing the technical data sheets (FT) for the different LW tools. There is therefore a compendium of working conditions and technical data sheets for each voltage range.

Before each operation, the work planner writes an operating procedure in accordance with the work to be carried out, the working environment, and the job-specific risk assessment. This operating procedure is logged in the work preparation that is monitored by the work supervisor during the execution phase. This approach, referred to as the “French method”, offers a tailored solution to each individual operation.

Broadly speaking, this method contrasts with the approach used in the English-speaking world, which hinges on predefined operating procedures for specific tools.

## STANDARDISATION: THE RISK OF LOWERING STANDARDS

The LW Committee authorises LW tools by means of technical data sheets. These technical data sheets refer to a baseline specifying the requirements that the tool must comply with, and the type tests required for its qualification. Whenever possible, and in order to minimise the cost of equipment, it is preferable to refer to standards. For live working, these standards are laid down by the IEC's TC78, CENELEC's TC78, and AFNOR's (French standardisation body) UF78.

As defined at the international level by the IEC, live working comprises all the apparatus used in the operation of electrical installations, and therefore covers both the tools for LW and the tools for work on de-energised parts and in the vicinity of live parts.

Since 2016, the IEC secretaryship has been held by France, or more specifically by SRECT. This role has allowed RTE to promote the French LW method (see box on the different LW strategies) by investigating the possibility of extending the scope of TC78 to perhaps include guidance on best practices for LW.

This function has also allowed RTE to enhance the monitoring of changes to existing standards, in order to prevent any slackening of the vigilance on requirements and testing methods, and to guarantee equivalent or better risk control.

At the European level, the secretaryship is also held by France and SRECT. Holding the two secretaryships guarantees consistency between the work carried by the IEC and by CENELEC. The task for CENELEC is primarily to align the standards for personal protective equipment with European regulations.

### A changing context

The standardisation context is changing around the world and in Europe. Fewer and fewer system operators are participating in standardisation efforts, and hardly any supplier representatives remain. The participants have less and less knowledge of the phenomena at play in the design of LW tools and the elaboration of tests. This loss of know-how may ultimately challenge longstanding requirements and let standards slip to the lowest common denominator.

There are also signs that the English-speaking countries are determined to move towards the North American standards. But these baselines are generally very much directed at one type of technology, and rule out any changes. In addition, they stipulate lower requirements than those of the IEC's TC78, particularly in relation to tools such as insulating hoses.

Overall, it is becoming difficult to find subject-matter experts who are competent and open to ensuring that standards continue to be upheld at the IEC and CENELEC.

No scientific work is being conducted today at CIGRÉ. The focus is on standardisation. However, in the last few years, work has been done on the organisation of LW (management, training).



### Further reading

- **LW Committee website:** [www.comite-tst.com](http://www.comite-tst.com)
- **SRECT website:** [www.srect.fr](http://www.srect.fr)
- **Travaux sous tension (Live working)**, C. Atlanis, S. Chabin - Techniques de l'Ingénieur publication (2017), reference D4140 v4

# THE DYNAMIC OPERATION OF ELECTRICITY NETWORKS, OR, WHEN IT HAPPENS TOO FAST FOR HUMANS

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**Vincent SERMANSON**

Distinguished Expert, Dynamic Operation of Electricity Networks

Aside from the societal and economic issues involved, the energy transition presents technical challenges and for this transition to be truly effective, priority must be given, among other things, to monitoring dynamic behaviours of the electricity system. Though an hour-by-hour assessment is adequate for capturing changes in the generation-consumption balance and the major determinants of the energy transition, it is necessary to zero in on smaller units of time (a few milliseconds or seconds) to ensure that automated systems operate correctly. These systems respond long before human beings become aware of the phenomena, in order to maintain network balance and resilience at all times. With the energy transition, this will become a more delicate balance, and accordingly, automatic dynamic systems have to be designed as of now.

## The dynamic operation of electricity networks addresses the stability of rapid interplay between constituents of the electricity system for which human or market reactions are excluded (response times of less than a few minutes).

The electricity system does not stop short at RTE's boundaries: it is a huge machine made up of all interconnected networks (foreign power systems, transmission systems, industrial systems) and of all devices connected to it by physical laws (electrical, electromechanical, electrochemical), from the turbine in a nuclear power plant to a LED screen at home.

The instrumentation and control systems for these devices (turbine speed control, battery charger) are designed to perform local functions, but interact via the electricity networks. Some of these interactions can be unstable in particular, fortunately rare, conditions: some electrical quantities can experience drifts or oscillations that are not damped, or are poorly damped. These instabilities can cause premature wear-and-tear, damage, even failure of equipment, and potentially harm or kill people.

Equipment protection devices minimise the most serious risks (harm to people, failure of equipment) so that, in practice, the consequence of instability is the disconnection of components (network, production, consumption, or storage components).

### Financial and reputational costs

For RTE, the challenges can take different forms. If the disconnections were frequent, they would degrade the quality of the electricity supply, which could give rise to compensation claims. The customers who can relocate their sites (datacentres) might then seek a better-quality product in another network. Long term, the company's image with customers could deteriorate and thus erode the company's legitimacy and the positions that it defends (NTSO, ITO<sup>1</sup>).

Furthermore, if it became necessary to fall short of the economic optimum in order to guarantee stable operation (through a reduction in exchanges,

or in the production of French renewable energy, or the imposition of group taxation for gas), this would entail costs. Financial costs, as well as costs in terms of CO<sub>2</sub> emissions, of long-term corporate image and credibility, and even legal and financial costs (European Commission sanctions, for example).

Furthermore, in the event of equipment failure, repairs often take time (particularly for transformers, and underground and submarine cables), requiring cuts in generation to guarantee the power system's continued operation in degraded mode.

Lastly, extensive load shedding (as happened in Great Britain in August 2019, or in the Iberian Peninsula on 24 July 2021) or a large-scale blackout can occur in the event of widespread system instability (loss of synchronism, frequency drop, non-damped inter-area oscillations).

The French electricity network has not had a large-scale blackout since 1987<sup>2</sup>. RTE's customers recognise the French transmission system's good quality electricity. But the system's greater operating range on the one hand, and the roll-out of power electronics on the other hand, may increase the possibility of a blackout and impair system reliability, if RTE - and the interconnected power systems - do not pre-empt certain phenomena.

1. ITO: an independent transmission operator is a TSO that owns the system it operates.

2. The French electricity system was not responsible for the November 2006 system disconnection of the European network.



# ○ The roll-out of power electronics and information technology

From the 1960s to the 2010s, RTE's use of power electronics was limited to a few system components (HVDC, SVCs). Since the 2010s, with a major integration of renewable energy production units, interfaced with power electronics, there has been broad dissemination of these devices across the electricity system. Among other things, the HVDC connection of offshore wind farms will become more widespread and create new problems.

Energy usage is also transitioning to electronics (household appliances, electric vehicles). From now on, a 100% power electronics network – or one serving a very large region – is no longer inconceivable (the European **MIGRATE** project).

Power networks are increasingly turning to the flexibility enabled by power electronics and information technology for real-time production-consumption balancing. RTE's certification of vehicle-to-grid technology in early 2022 is a concrete example.

## A range of issues

These advances present several characteristics in terms of rapid phenomena. Firstly, power electronics relies on components that are very fragile and costly: transistors. Complex systems ensure their protection and optimal use, but may generate unexpected behaviours that could include the disconnection of the whole device.

The second effect is the “black box”. This is the instrumentation and control system (its structure and its parameters) devised by manufacturers, which dictates the behaviour of a device. Although some characteristics are governed by codes and standards<sup>3</sup>, these do not cover everything, and the details of the instrumentation and control systems are the industrial intellectual property of the manufacturers.

Power electronics modelling and simulation raises issues about the availability of models from RTE's customers, the validation of these models, and the efficiency and accuracy of the simulation tools (offline or real time).

New types of instability may then arise: unstable interactions between high and low frequency

instrumentation and control systems, or harmonic instabilities (at frequencies that are multiples of 50 Hz).

The connection of offshore wind power via HVDC lines gives rise to new problems. The first task is to deal with the technical issues (poor damping due to underwater instrumentation and control systems and cables, the scale of offshore wind farm connection networks). Secondly, the presence of several technologies and manufacturers creates interoperability issues. In addition, the size of the installations themselves and their prospective connection to the land-based alternating current network puts the whole system at risk.

Lastly, most of these devices are linked to the distribution systems through the connection of renewable sources. Requirements for the latter tend to be less stringent, as the distribution systems rely on the transmission system for stability (as a source of voltage amplitude and frequency).

However, new functionalities or levels of performance are now accessible thanks to the flexibility of power electronics, and may promote a high penetration of renewable energies (see box on grid forming). One of the challenges for transmission network operators (TSO) is to define the desired behaviours while remaining neutral in their choice of technology.

## Ongoing upstream studies and analyses

With power electronics, new solutions produce as many answers as they do questions, and preliminary work is needed to assess their effectiveness and limits through digital simulation.

RTE insists on the provision of replicas of the instrumentation and control systems for the large components of its network (HVDC, SVCs) or offshore wind farm fleets: it is the actual, physical instrumentation and control system, and not a model, that is made to interact with a model of the network, using a real-time simulation tool. This type of simulation has proved its usefulness, particularly in identifying issues with the Savoie-Piémont interconnection prior to commissioning.

3. The Requirements for Generators (RfG) code, HVDC code and their national adaptations.

Yet there is a continuing need for reliable models of renewable energy farms, for which RTE does not always have replicas. Furthermore, in the future, it will not be possible to have replicas of all the equipment. In addition to this, new challenges are emerging for the simulation of the most rapid phenomena<sup>4</sup>, which will have to be simulated in larger and larger networks with models provided by different manufacturers. There are efficiency and accuracy challenges in the conduct of these studies.

It is also necessary to have models and simulators that also work for less rapid phenomena<sup>5</sup>. One of

the challenges is the development and validation of generic models of renewable energies in order to carry out studies well before the models are provided by the manufacturers.

Regarding simulation, the open source, one-of-a-kind **Dynawo** platform, currently being deployed, draws on innovative solutions to improve the quality of results, transparency (the option of sharing the modelling in **Modelica**), performance (speed and resilience in degraded conditions) and flexibility of modelling (clear separation of modelling and equation-solving).

## GRID FORMING, A PROMISING SOLUTION

Power electronics provides great flexibility, through tailored control and sometimes design. This makes it possible to provide all the necessary services to the network. The inverters installed in the network already provide some system services (such as voltage or frequency regulation). If the objective is to increase significantly the penetration of power electronics, and perhaps to do without synchronous machines, even for a brief period, it is necessary to have new synchronisation services provided by so-called grid-forming sources.

A grid forming source (of which synchronous machines are an example) is capable of providing energy to a power system and to the connected loads in a stable manner and independently. In order for converters to perform these functions, it is necessary to adapt their controls and possibly combine them with a small power reserve. These sources would also stabilise a network in which there were too few synchronous machines.

In a collaboration with the Lille Laboratory of Electrical Engineering and Power Electronics (L2EP), the controls defined by the European project **MIGRATE** were tested on mockups to validate the first stage of deployment.

Using demonstrators installed on the network, the **OSMOSE** project has provided evidence that a battery could deliver grid forming services. In the **RINGO** project, an inverter and battery made it possible to start-up an islanded system with a wind farm, to operate it for several hours, and then to reconnect to the main network.

There are various mature grid forming projects overseas. In Scotland, a 70 MW wind farm operated in grid-forming mode for several months. In Norway, with the Johan Sverdrup project, two HVDC connections from different manufacturers are in grid-forming operation and supplying an offshore alternating current system at sea, several hundred kilometres off the coast.

If the intention is a fast roll-out of the grid forming solution, then this requires amendments to the connection rules – initially designed for synchronous generators or standard converters referred to as grid following devices. Work is underway at ENTSO-E to begin its incorporation into the next version of the connection codes.

4. Electromagnetic transients with time constants of the order of a few microseconds.

5. Electromagnetic transients with time constants of the order of a few milliseconds to a few seconds.

## Network control and investment

The connection rules for generating facilities are being adapted to the new solutions, to new phenomena, and to operating experience, but consultation and the implementation of network codes is a slow process<sup>6</sup>. It is therefore necessary to identify and systematise desired future equipment behaviours, of which today there are few, but may be many tomorrow.

The behaviour of production connected to the distribution networks plays a major role in the management of incidents. Sharing knowledge of the behaviours of generating facilities and consumers with the distribution system operators (DSO) is central to the management of risks.

As regards investment, thought must be given at a very early stage to dynamic behaviours. Investment in the transmission system improves the resilience of the system (high-speed circuit breakers, series capacitors,

capacitor banks, shunt reactors, synchronous compensators, SVCs, STATCOM, HVDC). But the service provided by these devices is very difficult to monetise, which is hindering their insertion into the French system, as any substantial investment requires a cost-benefit analysis.

Furthermore, the protection scheme will also have to be adapted. Solutions are available, particularly teleprotection functions. It is less a matter of conducting studies than of defining an industrial deployment policy.

## More varied, volatile and extreme situations

Both at a European and a local level, network usage has changed primarily as a result of the massive and rapid development of renewable energy, and the shutdown of nuclear and coal production in a network that is changing much less. The statistical distributions and time variations of flows across installations have changed and become more variable (standard deviations) and more volatile (time drifts), with more extreme cases (min/max).

In addition, centralised generating facilities are less in demand from the market. Yet they ensure voltage and frequency control, provision of inertia, and various other sources of stabilisation (synchronism, mitigation of inter-area oscillations). The ageing of the French nuclear fleet is decreasing the overall availability rate, and making the absence of 5 to 8 units in one same area a realistic possibility (prior to the 2021/22 winter episode, which was untypical due to Covid, 8 units had already been simultaneously unavailable in the winter of 2019-20, in the North-West).

The isolation procedures to allow maintenance work could also be affected by poorer predictability of suitable periods (primarily due to the variability of renewable energies). Maintenance windows could become extended and/or have to be moved to wintertime. Furthermore, with the growing need for replacement work across the electricity system, additional work on existing installations (high voltage HTB1 and HTB2) will be needed.

All these changes make it necessary to adapt the topology accordingly, and in real time, which adds additional layers to the different possible situations. Situations that give rise to requirements for control that are more varied, more difficult to predict, and on the rise.

This greater probability of challenging situations calls for a re-examination of certain models or methods that are implicitly based on past experience. For example, increased flows modify the assumptions for the calculation of transient overload capacity installations<sup>7</sup>.

6. Consultations on the European Network Code RfG V2 are planned for the end of 2022. This new version will enable the introduction of requirements for storage and grid forming.

7. Transient overload intensities are being revised as part of the ACTIVIA project.

### Rethinking the likelihood of failures and unavailabilities

The electricity system is going to face increasing uncertainty, and the likelihood of increasing failures and unavailabilities: system equipment is ageing, and trade-offs will be required for replacement operations, given the financial and industrial scale of the phenomenon. Furthermore, increasing demand on generating facilities, predominantly in a reactive manner, can increase maintenance periods or impair their reliability (the wear on Francis hydro-turbines, vibration of generator rotors in nuclear generation units).

Lastly, the wider range of situations increases the time spent in conditions that are largely uncharted, which present little danger in theory but in which malfunctions could be serious. Common modes become more likely, and hidden faults or atypical operating modes can have more severe consequences. For example, when a large number of installations are carrying more load than usual, there is a greater likelihood of activating an improperly set protection, or of an inability to loop the network due to excessive differences in angles; and successive trips of the installations, due to transfers of electricity flows from one to the other, are also more likely. Finally, it would be more difficult to control the effects (segregation of areas with large production-consumption imbalances, mix of frequency and voltage problems, as on 24 July 2021).

### Review of standards and risk assessment methods

Another source of uncertainty lies in being closer to the limits. Prior consideration of the method for measuring and controlling risk would be advisable. This reflection should take into account several factors of change such as the variability, the volatility and the extreme nature of these situations. It is also important to look into the new phenomena associated with power electronics, with the interwoven nature of physical systems and new information technology (including controllers), and with man-machine interactions. Finally, societal needs and expectations (economy, competitiveness, resilience) must be factored in. Although RTE is fully aware of these changes in the situation, increased vigilance is called for in order to minimise the risks arising from a lack of preparedness.

## KEEPING A CLOSE EYE ON LOW-FREQUENCY OSCILLATIONS

In the last few years, there has been a fresh upsurge in inter-area oscillation phenomena. These are low-frequency oscillations (from 0.1 to 1 Hz) between the rotors of generators located in the outermost parts of Europe, which are triggering oscillations in active power flows in some network installations, and can reach several hundred MW. This was the case, for example, on 11 October and 10 November 2021 (Spain – Central Europe) and on 5 January 2022 (Italy-Denmark). These phenomena are associated with greater long-distance power flows in the network, as well as the increased contribution from scattered production units.

Studies have indicated that mitigating measures are required to lower the risk of dangerous oscillations (reduced damping) for Ukraine's connection to the European network.

The **SURVOSCIL** project launched by RTE in 2022 will ensure the detection of poorly damped or high-amplitude oscillations through the continuous monitoring of PMUs<sup>8</sup> processed by an algorithm developed by Washington State University (USA).

Once poorly damped oscillations are identified, the challenge will be to pinpoint the most effective actions to counteract them, both in real time (modification of the production plan) and over the long term (investment in synchronous compensators, in STATCOMs, or in batteries with individual settings). Because of their distance from the centre of Europe, Italy and Spain are now deploying or considering such investments.

One key to deciding what investment is needed, despite growing uncertainty, is being able to perform a larger number of dynamic simulations. Trials are underway (SEDRE, CNES, R&D, CNER) with hundreds of simulations of voltage collapse, high voltages, electromechanical stability, or electromagnetic transients.

8. Phasor measurement unit: high-precision GPS-synchronised voltage measurement.

### Real-time monitoring of stability

Given that not everything can be foreseen, RTE is gearing up for more and more real-time monitoring. In 2019, CNES implemented the systematic analysis of transient stability. The close-to-real-time simulation of hundreds of cases is now possible. This process systematically tests simple corrective actions, with analyses covering approximately 80% of cases.

An additional approach involves using simplified indicators that can be quickly calculated, to a calibrated level of reliability. They would sweep through more situations ahead of time, identify the most critical weaknesses and put forward real-time corrective actions more promptly, particularly in exceptional situations (a packing snow event, for example). Work is in progress at the University of Liège on the so-called dynamic security assessment (DSA) and EEAC<sup>9</sup> methodology.

## Exchange and forward-planning across all specialisms

European cooperation will be a key component in controlling dynamic operation, with the convergence of common standards, sharing of information and models, and the coordinated distribution of stabilisation mechanisms (fast reserves and inertia). Furthermore, in the event of an incident, the TSOs can play a role by implementing rapid levers for action at a Europe-wide level, such as reducing flows. With its central geographical location and technical standing, RTE is well placed to lead the way.

All the specialisms within the company must continue to anticipate developments in the system. For example, regarding the connection of large power units (offshore generation, heavy-user industrial facilities), RTE must plan ahead for the system's future needs, particularly in terms of auxiliary services. Aside from the development and maintenance of simulation tools, it is vital to enhance expertise in modelling and the use of these tools. In that

respect, the expertise gained abroad, primarily via RTEi, is a very useful springboard for practical work on issues that other TSOs are currently facing, and which will soon arise for RTE, particularly in relation to offshore wind power.

The development of power electronics must not distract from the need to maintain expertise on the behaviour and modelling of synchronous machines and their upstream processes, of which there are now and will remain many (there are 300 hydro-generation sets connected to the HTB2 or HTB3 high voltage networks). Cross-cutting skills in power electronics, protection planning, and stability studies will become increasingly important. The challenge is to continue developing an all-round culture of electrical engineering, which would make for earlier detection and even faster responses to some challenging situations.



### Further reading

- **Fonctionnement du système électrique (Power system operation)**, RTE safety guide
- **Notices techniques du service du transport : fonctionnement des réseaux en régime perturbé ou transitoire (Technical notes on the transmission system: network operation with disturbances or transients)**, [R-TSP-CNER-SETP-NTT-78-00516.]
- **ENTSO-E reports on the incident of 24 July 2021**
- **Grid Forming: OSMOSE-D3.3 Analysis of the synchronisation capabilities of BESS power converters**  
<https://www.osmose-h2020.eu/>

9. Extended equal area criterion



# THE ELECTRICITY SYSTEM: A SYSTEM OF SYSTEMS, A CYBER-PHYSICAL (R) EVOLUTION IN PROGRESS

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**Patrick PANCATICI** | Scientific Advisor

The large electricity systems are now more than ever cyber-physical systems of systems. Cyber-physical systems theory can help RTE understand some of the issues of the energy transition, perhaps even find solutions. But it presents scientific challenges in analysing and designing interactions between the “cyber” part and the “physical” part.

Cyber-physical systems theory provides a robust framework for modelling, analysing, and designing real engineering systems that integrate communication, control, and computation capabilities (the “cyber” part) into a natural and/or artificial (man-made) system governed by the laws of physics (the “physical” part).

America’s National Academy of Engineering considers electrification to be the greatest achievement of the 20<sup>th</sup> century<sup>1</sup>. The Academy believes that large power systems are the most complex machines ever built by humanity. Since their creation, they have been the most emblematic examples of systems of systems: thousands of large generating units interacting with millions of electrical loads through long-distance connections (electricity networks).

In the past, electricity could not easily be stored in that form, and the supply-demand balance had to be addressed almost moment by moment (in a time window of a few seconds). This daunting problem was neatly resolved by the synchronous generator<sup>2</sup> producing alternating electrical current and voltage.

Voltage and current are sinusoidal signals oscillating at a given frequency ( $f$ : the nominal value in Europe is 50 Hz). This electrical frequency is proportional to the rotation speed of the synchronous generator. When large numbers of synchronous generators are connected to the electricity system, they are “magically” synchronised thanks to the structure of their interactions through this alternating current (AC) electrical network.

In the event of a sudden change in the system, these synchronous generators are temporarily unsynchronised but generally return to synchronous operation<sup>3</sup> within a few seconds. Their speed of rotation matches the frequency of the power network, which, in steady state, is the same value across the whole system. This frequency provides information on any imbalance between generation and load: if it is above the nominal frequency then too much power is being injected into the system; if the frequency is below the nominal frequency, this means that there is insufficient power being injected.

By measuring its rotation speed, an individual synchronous generator is “aware” of the overall imbalance of the system and “knows” that it must increase or decrease its power output. This is the reason why large power networks have been able to ensure a reliable power supply without a complicated telecommunications system and without a centralised control system, even though electricity could not be stored (though in fact a small amount of kinetic energy is stored). In effect, this is a highly resilient distributed control system, with all the synchronous generators in a vast area (for continental Europe, for example: from Portugal to Poland, or from Denmark to Greece) contributing to the control process. In the event of the unplanned disconnection of a large generator (1 GW), the thousands of other generators will instantly (within a few seconds) and automatically compensate for this loss of supply by each generating a small amount of additional power (a few MW).

### Like an ant colony

This is what typically happens in systems of systems when a large number of agents, physically connected (in this case, by an electricity network), contribute efficiently to a common objective (here, supplying electrical loads). The comparison with an ant colony offers a parallel with the role of “frequency”, which is similar to a “stigmergic”<sup>4</sup> path. An ant finds food and marks out a pathway by leaving traces (pheromones) in the environment to mark the route back to its nest. Other ants follow this path and reinforce it further by leaving more traces, thereby maximising the search for food. This is an efficient process for finding food and thus contributing to a shared objective.

The “frequency” in an electricity system is similar to the “pheromones” of an ant colony. This is one of the

1. <http://www.greatachievements.org/?id=2949>

2. It first appeared in the early 1880s, based on the principles discovered by Michael Faraday in 1831-1832.

3. There is a limit: loss of synchronism can occur in case of too long a short-circuit in the vicinity of a synchronous generator.

4. The biologist Grassé coined the term “stigmergy” to describe the indirect flow of information between members of a termite colony, as they coordinate their nest-building activities.

main surprising properties of traditional alternating current networks. But the introduction of ever-growing numbers of components interfaced with power electronics may challenge this fundamental principle. Various projects across Europe and the United States have thrown light on these issues and put forward new solutions<sup>5</sup>.

It is not easy to guarantee an appropriate level of reliability for an electricity system, while keeping costs under control. Finding the right balance between reliability, cost and sustainability brings into play political decisions that attempt to monetise “reliability” and “sustainability”.

### Digitalisation as a cornerstone of system security

In traditional electricity systems, the “cyber” layer (information and communications technology) was used primarily to optimise the system, but not

to guarantee its security or its stability. Local protection and controls were very simple, and were implemented via analog devices. They have now been digitised, without really changing their functions or the basic concepts.

In order to optimise the system, slow centralised controls were installed, using minimum remote information and actions, and requiring only low-performance telecommunications systems (low bandwidth, high latency, average reliability). System reliability was not significantly impacted by failures in this traditional “cyber” layer.

Today, we are witness to a major development and perhaps a revolution in electricity networks. The term smartgrid is used widely, always without a very precise definition. The concept of cyber-physical systems of systems provides a useful framework for capturing the essence of this (r)evolution.

## ○ A (r)evolution in large power systems: the cyber-physical systems of systems

Electricity systems and their management have become more and more complex. The first reason is the massive integration into the power system of renewable but generally intermittent energy sources. Energy flows in the network are created by the changing locations of generation and consumption. With large quantities of intermittent production, the predictability of energy sources is reduced, thereby affecting the predictability of flows.

What is more, some of these new sources are small production units (as in the case of solar power, for example) that are connected to the distribution system and make it an active system (see example in box). The transmission system operators’ (TSO) observability of these power injections is limited, and the TSOs have no direct control over them.

There are also inconsistencies between the relatively short timeframe (5 years) for building new production units (wind and solar) and the time required for administrative procedures and for building new power lines (often more than 10 years in Europe).

In Europe, the best locations for wind farms are primarily along the coast and at sea, while solar generating facilities are best sited in the southern part of the continent. These locations do not generally correspond to major load centres. Long-distance transmission systems are therefore still needed. These networks will have to deal with the variability of flows brought about by the stochastic<sup>6</sup> nature of the new generating facilities.

5. For example: the European project Migrate (<https://www.h2020-migrate.eu/>) or SuNLaMP in the USA.

(<https://www.energy.gov/eere/solar/project-profile-stabilizing-power-system-2035-and-beyond-evolving-grid-following-grid>)

6. Subject to random phenomena.

### **The energy transition, but also public acceptance, electricity markets, and ageing assets**

The second reason why networks and network management are increasingly complicated is that it is more difficult than ever to build new overhead lines owing to low public acceptance.

The third reason is linked to the set-up of electricity markets that do not fall within administrative and historical borders. Producers, traders and consumers view electricity transmission systems as resources to which they should have unlimited access. However, this point of view may infringe on security considerations, given that service interruptions (blackouts) over long periods of time are unacceptable in our present-day societies due to their economic and social costs. Market players often see the TSOs' management of system reliability as a potential constraint on their activities and a possible curtailment in "European social welfare", rather than as a means of implementing their commercial transactions while conforming to the physical limitations of the system.

Finally, the last reason is that the ageing of grid assets calls for greater attention. A significant proportion of European grid assets are more than 50 years old. Managing and maintaining these assets in systems that have to provide continuity of service can become extremely difficult and must be planned for when large numbers of assets are simultaneously reaching end of life.

### **Rethinking system fundamentals**

In order to protect the security of supply in this context, the TSOs must modify the system architecture and give careful consideration to direct current technologies (HVDC). They must also optimise

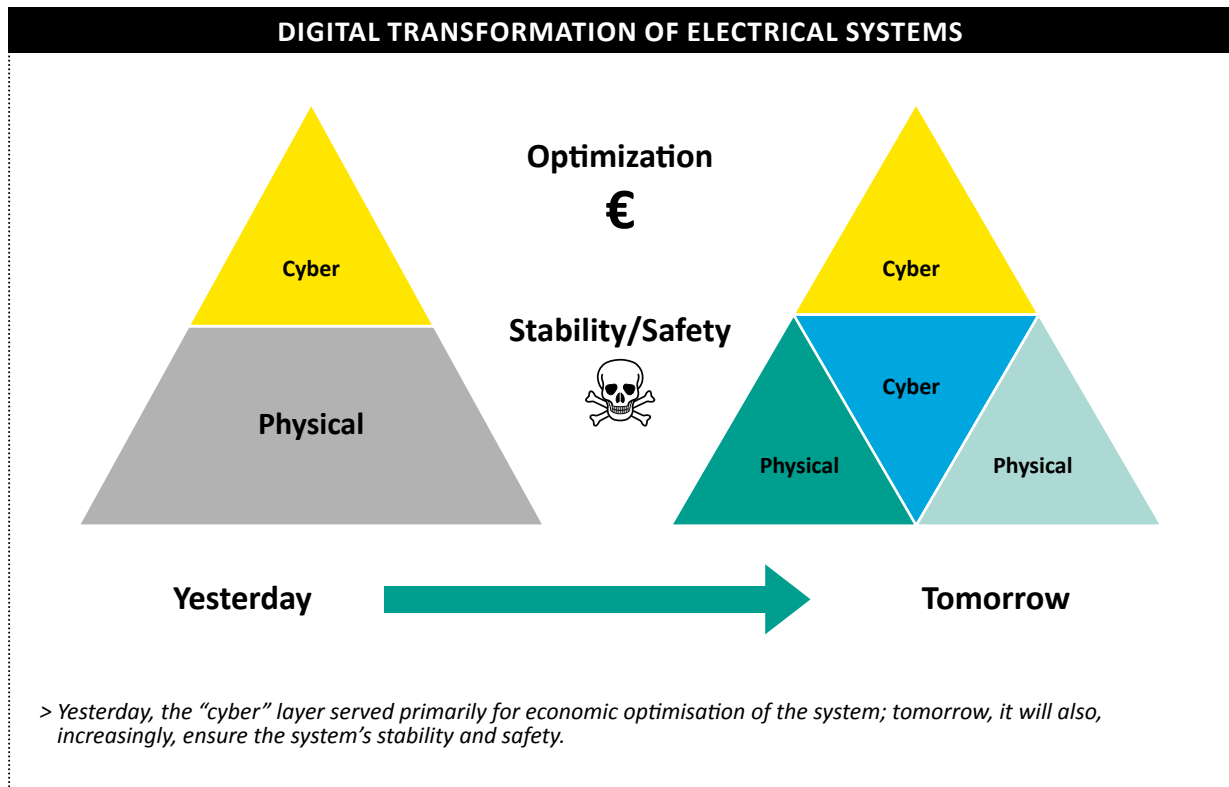
existing systems by adding more and more special devices (such as phase-shift transformers, static var compensators, and advanced measurement, control and protection systems) and by harnessing the flexibilities provided by these new network components.

At the same time, managing the consumption or storage of electricity could offer new ways of controlling the system, even if the associated business models are yet to be clarified. In any event, the way in which these flexibilities are put to use will require a rethink of the traditional operating practices that were based on the assumption that load was an uncontrollable random exogenous variable, and that it was impossible to efficiently store electrical energy.

All these developments are changing electricity systems more than ever before into cyber-physical systems of systems (CPSoS). The "cyber"<sup>7</sup> layer will play a vital role in system reliability. Indeed, more and more active controls are embedded in subsystems that become "smart" systems and partially autonomous. System behaviour will be determined by the interactions between these "smart" agents operated by local software (blue triangle in the illustration) rather than by the laws of pure "physics".

The "cyber" layer ensuring the reliability of the system must therefore be designed with great care, by properly incorporating the concept of CPSoS (see example in box). A close watch should be kept for any sign of the emergence of possible negative effects that may occur on reaching a given critical level of penetration of new "smart/autonomous" systems. This is not an easy exercise and the TSOs will have to specify behaviours which yesterday were determined by the laws of physics and did not need any specification, but which tomorrow will be defined by the software in local controls.

<sup>7</sup> Layer based on algorithms, software, computers, and telecommunications networks (ICT).



## THE EXAMPLE OF “ACTIVE” DISTRIBUTION SYSTEMS

The transformation of distribution systems (the last few kilometres of network at low voltage) into “active” distribution systems is an example of this (r)evolution. More and more small production units and electrical batteries are connected to these networks. There are schemes that try to encourage consumers to adapt their usage to “help” the system. More and more controls are installed in the distribution networks, thereby transforming them into active systems.

In the past, distribution systems were “passive”: they reacted instantly to electrical signals in accordance with the laws of physics. The amount of power used was stochastic. However, by way of example, the relationship between power consumption and voltage magnitude was captured sufficiently accurately by simple aggregated models: generally speaking, decreasing the voltage lowers power consumption, which enhances the resilience of the system.

In the future, the voltage magnitude in distribution systems will be controllable thanks to all the power electronics connected (this is already the case for some equipment). But if these controls are too rapid, power consumption will remain constant, and that useful relationship between power consumption and voltage magnitude will be lost. Too much local bias in the design of controls in distribution systems or electrical loads may have an adverse effect on the stability of large power systems<sup>8</sup>.

8. Contribution of distribution network control to voltage stability: A case study, P. Aristidou, G. Valverde, T. Van Cutsem - IEEE Transactions on Smart Grid (2017)



## ○ CPSoS research challenges

Some of the issues related to electricity systems present research challenges that require the joint efforts of the control, computer science and optimisation research communities.

The main issue is tied to the approximation and reduction of large complex systems, which represents an unavoidable stage in the design of efficient control strategies for large power systems. One key challenge is the introduction of stochastic aspects in the reduction and approximation methods. Different approaches have been put forward, but no attempts appear to have been made yet to apply these types of advanced methods to large power systems.

Since their emergence, electricity systems have been large systems of systems governed by hierarchical control systems (primary/secondary/tertiary)<sup>9</sup>. In the past and until recently, local controls were relatively simple, and the hierarchy was limited to two or three levels. Today, the energy transition is driving a shift towards increasingly dispersed generation and distributed, advanced controls. The upper layer of controls must be aware of the existence of “smart” features embedded in subsystem edges.

In the upper layer of controls, some decisions must be taken early in view of the time needed to implement certain actions. For example, a decision has to be made at least eight hours in advance on whether to connect a thermal plant to the network, or again, to postpone maintenance work requiring the disconnection of some power lines. A simplified modelling of grid capacity must also be provided in advance to the day ahead and intraday electricity markets.

The approximation methods used in the upper layer of controls must factor in the “cyber-physical” dimension, that is to say, the open-loop physical systems (which are not equipped with controllers) but also all the embedded advanced controls, including the potential changes in their behaviour during disturbances (switching). New closed-loop controls (when a system is equipped with a controller) are being, and will increasingly be, implemented to deal with the uncertainties created by the massive integration of renewable energy generators.

These issues are difficult to resolve for a small system with simple dynamics but are well-nigh impossible to resolve for large electricity systems. Thus, approximations are needed in order to produce approximate solutions for these issues. But some guarantees (mathematical proof) of the results obtained would be required. For example, the guarantee of a “conservative” approximation, in other words, that the “optimal” decisions put forward would definitely lead to an actual level of risk that is lower than the admissible risk level. At the present time, these decisions are mainly based on the say-so of experts who seek the right decisions by relying entirely on simulation tools and not optimisation tools.

### Human-machine partnership

The issue is inherently complex and will become even more so. Software assistants will therefore be required to help the operators deal with this complexity. The partnership between these assistants and the operators is a key question that calls for detailed consideration<sup>10</sup>.

Another important aspect is the control of a large population of devices or agents (for example: organisational entities) with partial autonomy. Contracts should encourage individuals to adapt their behaviours in response to certain signals (incentives, price). However, in order to define these contracts, it is important to be able to model - using game theory<sup>11</sup> - their impact on the behaviours of individuals, as a means to maintaining the “multiplexing gain”<sup>12</sup>, which is a traditional and natural advantage of large electricity systems.

There is also a risk of possible synchronisation of agent behaviours, and mechanisms must be designed to try to prevent this synchronisation, which creates conflicts for access to the finite capacities of electricity systems. In the past, system defence plans were drawn up for electricity systems to address this type of “blocking”, but they need to be reviewed in the context of the energy transition, by drawing on advanced information and communications technologies. Designing these new defence systems

9. A relatively slow high-level controller provides instructions to a faster-acting low-level controller, which adjusts to hazards.

10. *Repenser l'interaction entre l'humain et la machine (Rethinking human-computer interaction)* Wendy Mackay – Chair on Informatics and Computational Sciences at the Collège de France (2021-2022)

11. *Direct interaction between agents, without a central organiser.*

12. *During normal system operation, the uncorrelated or even anti-correlated behaviours of agents yield a physical capacity that is below the sum of the maximum physical capacity used by any one individual agent.*

is not straightforward and requires certification of their effective operation in very infrequent stressed conditions.

This certification relies on relevant approximations (since it is impossible to solve the “real” issue) and the meaning of the word “relevant” must be clarified. These approximations should be determined by the question being addressed. No single approximation can be right for answering all the questions.

Automatic learning systems (machine learning) are very prominent today but, in general, these methods can offer no guarantee of proper functioning. Despite this, they have proved very successful for some applications (image and sound processing, natural language processing) and they may prove useful for “optimising” the system.

When trying to design a control strategy, there must be a guarantee that the modelling used is causal modelling, in other words, that a particular cause does indeed produce a particular effect, and not

vice-versa, or that the model is not merely reflecting spurious correlations. Automatic learning methods can be used if the consequences of an error are not profound, or if it is possible, using models based on the laws of physics, to verify that the decisions put forward are not hazardous.

Overall, it is essential to clearly establish how the system states can be kept within acceptable ranges. In order to achieve this, there must be guarantees, as there are significant risks: risks to people and property, explosion, destruction, cascading failures, blackouts, etc. Once these guarantees have been secured, an economically “optimal” operating point can be sought.

Cyber-physical systems theory provides a framework for finding answers for our large power systems. The solution will undoubtedly come from a mix of different approaches (based on physics and on data) in order to address the growing complexity brought about by the energy transition.



## Further reading

- This paper is translated and adapted from the *Energy Systems* section in the article **Position paper on the challenges posed by modern applications to cyber-physical systems theory**, collection of papers - ScienceDirect (2019)
- **Power System Stability and Control**, P. Kundur - McGraw-Hill (1994 - 2<sup>nd</sup> edition due for publication in 2022)
- **Causality: Models, Reasoning, and Inference**, J. Pearl, Cambridge University Press (2009)
- **The Behavioral Approach to Open and Interconnected Systems**, J. C. Willems - IEEE Control Systems Magazine (vol. 27, no. 6, Dec. 2007)

# ARTIFICIAL INTELLIGENCE IN THE MANAGEMENT OF THE ELECTRICITY SYSTEM

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The management of the electricity transmission system is becoming increasingly complex, particularly with the integration of intermittent renewable energies and the transformation in electricity uses (electric cars, self-consumption). Although RTE has always stitched mathematics and information technology into its decision-making processes (optimisation of the transmission network, projections of electricity flows), the management of this growing complexity requires an ever-greater hybridisation of physics and digital methods. By virtue of its prospects and its maturity, artificial intelligence opens up new opportunities.



**Artificial intelligence (AI) is defined as the ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings<sup>1</sup>.**

Although the origin of the concept and term AI is the subject of much discussion, there is broad agreement on the importance of Alan Turing, John McCarthy and Marvin Lee Minsky. Turing envisaged endowing a machine with a kind of intelligence. For his part, John McCarthy was the first to use the term artificial intelligence, and he and Marvin Minsky were the main organisers of the 1956 Dartmouth Conference, which proved to be the founding moment of artificial intelligence as a separate field of research.

AI, often thought to belong to the field of cognitive sciences, cuts across many disciplines, particularly computational neuroscience, computer science and mathematics. Although it lays claim to being a separate field, AI has the distinction of being transdisciplinary and bringing together competencies in “hard” sciences but also in psychology, linguistics, philosophy and anthropology.

Since it first appeared in 1956, the term artificial intelligence has caused disquiet in the scientific community. The term augmented intelligence may be more appropriate, as it includes the concept of a data-based decision-making aid at mankind’s service.

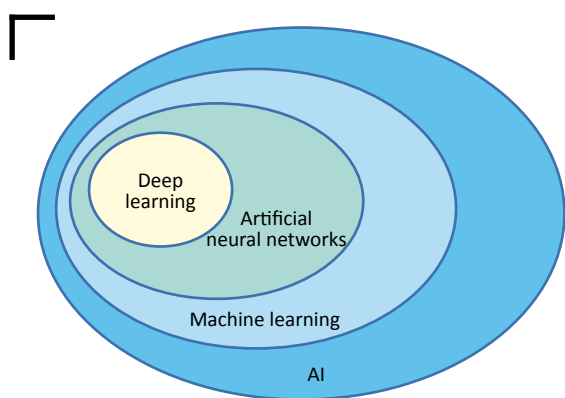
no doubt explains the common confusion between AI and machine learning. Also known as statistical or automatic learning, machine learning is the AI field that aims to give computers the ability to “learn”.

Its uniqueness lies in how it generalises: unlike physical or probabilistic models, machine learning does not specify rules in advance but seeks to attain a kind of universality. Its methods are drawn from many different fields: theoretical computer science, optimisation, probabilities, statistics, signal processing, etc. This learning often requires large amounts of data.

There are several types of learning: the most common are “supervised” learning, which aims to predict/classify, and “unsupervised” learning, which seeks to discover possible structures (relationships). “Reinforcement” learning, spotlighted during the Google DeepMind Challenge match in 2016, involves an autonomous agent<sup>3</sup> learning the actions to take, using acquired experience, so as to maximise a cumulative reward. Lastly, there is “transfer” learning: it consists in leveraging previous learning to solve a comparable but different problem.

### Machine learning

AI methods include expert systems<sup>2</sup> and above all machine learning, which is currently centre stage; this



### Artificial neural networks

Artificial neural networks are one of the fundamental tools of AI. Inspired by the functional aspects of biological neurons, these models are the most frequently used in the world of data. Some networks specialise in processing images or text (convolutional and recurrent neural networks). These neural networks can also be made to compete using generative adversarial networks (GAN).

Today, artificial neural networks are able to use deep learning. Algorithms use several layers of non-linear processing units and learning occurs at multiple levels of detail or of data representation. Deep learning has greatly improved the processing of images, sounds and text.

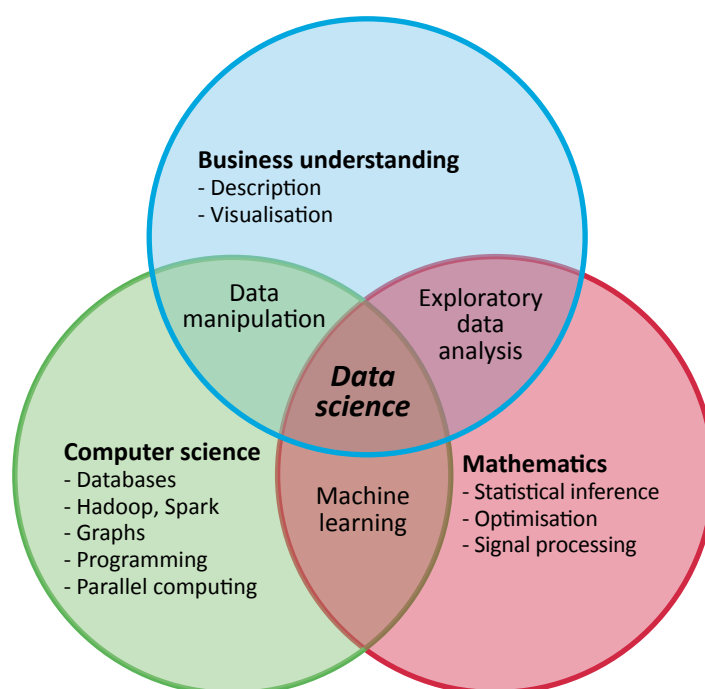
These AI models are often used by data scientists who have different skills: business understanding of data, computer science (including data storage) and mathematics.

1. Definition in Britannica, 2022

2. An expert system is generally defined as containing a knowledge base, an inference engine, and an user interface

3. An information system that operates without third-party intervention.

## DATA SCIENCE



### AI today

After several winters owing to technological and scientific obstacles, AI is enjoying extraordinary exposure, not only in the professional sphere but also among the general public. Media coverage of victories of machine over man at chess (Kasparov vs. Deep Blue, 1997), at Jeopardy (IBM-Watson, 2011) and at Go (Lee Sedol vs. Google-AlphaGo, 2016) has sparked great interest.

Search engines, chatbots, voice assistants and smart image libraries have also raised the profile of AI. There are many other examples of practical applications. In the field of medicine, AI can help with the diagnosis of diseases (through image analysis in particular); in the area of transport, it can assist with traffic management and support the development of autonomous vehicles. In the context of security, AI is put to use for facial recognition.

Although its image is ubiquitous, the myths surrounding AI must however be debunked. It is not the recent phenomenon one might think: AI actually stems from much earlier work in mathematics and information technology. Recent achievements have been made possible in particular by increases in storage capacity and computational resources.

### AI is not infallibly effective

AI is energy-consuming and highly specialised. Although machine can outperform man in basic tasks, it cannot match the efficiency and versatility of man. What is more, it is energy-intensive: as stated by Luc Julia, creator of Siri, the Google-AlphaGo

## AI AND DATA SCIENCE: SPOT THE DIFFERENCE

Although they have many similarities, data science is distinct from AI:

- Expert systems belong to the field of AI, and not data science.
- Sampling methods belong to the field of data science, and not AI.
- Data preparation and understanding, so central to data science, is less prominent in AI.
- Data science can address one-off studies, over one day, without seeking to set up a permanent decision-making aid process.



programme consumes 440,000 Wh compared to 20 Wh for the human brain.

Finally, AI is not infallibly effective. The work on autonomous vehicles has flagged up problem areas such as robustness, in other words, their resilience to disruptions. Algorithms can also be subject to learning bias, which may restrict their applicability and give rise to ethical questions. Furthermore, some issues cannot be resolved owing to insufficient data.

AI must be regulated like any other technology. Many would like to create or enhance the ethical framework for AI support of storage and use of personal data (such as the GDPR<sup>4</sup> for example).

AI is unquestionably transforming, and will undoubtedly transform, the job market, just as coal and robots once did. It will not be possible to take advantage of the opportunity to alleviate certain repetitive and less creative aspects of work without also supporting social change through awareness-raising and workplace training. Furthermore, initiatives such as **AI for good** aim to put AI to work for the benefit of social innovation (environment, health, education) in concrete ways.

## **A PROACTIVE FRENCH STRATEGY**

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In 2018, France stated its ambition to become a leader in artificial intelligence with its strategy entitled **AI for Humanity**. The commitments of this strategy are the following:

- **Bank on French know-how:** Enhance and promote existing national expertise (a wealth of French researchers and engineers, establishment of laboratories in France: Facebook, Google, Huawei, IBM...) by equipping research with additional computing resources (e.g.: 10 petaflops for IDRIS, the Institute for Development and Resources in Intensive Scientific Computing) and by establishing Chairs (coordinated by INRIA, the National Research Institute for Digital Science and Technology), technological research institutes, interdisciplinary research centres (3IA, Interdisciplinary Artificial Intelligence Institutes), etc.
- **Pool assets:** Optimise the use of centralised databases in France to foster and disseminate innovation
- **Establish an ethical framework:** Establish a group of international AI specialists, similar to the IPCC.

This cross-party political determination is conducive to knowledge sharing between research centres (public and private), large companies and start-ups, and to building up expertise in AI. The French ecosystem includes in particular France Hub IA, the technological research institutes, and the 3IA laboratories (Interdisciplinary Artificial Intelligence Institutes).

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4. General Data Protection Regulation

## AI in RTE

Applied mathematics has historically been used at RTE for electricity consumption forecasts, renewable energy production forecasts, or network optimisation. Going forward, the company is developing AI solutions for operational purposes and data science studies. The aim is to make full use of the technological opportunities presented by mature AI.

Data processing draws a distinction between “automation” (systems that perform basic and/or laborious tasks much faster than humans can) and “augmentation” (systems that enhance human cognitive performance). It is important to ensure that a given solution has the level of automation and augmentation appropriate to the complexity and characteristics of the problem.

### Meeting the requirements of specialisms

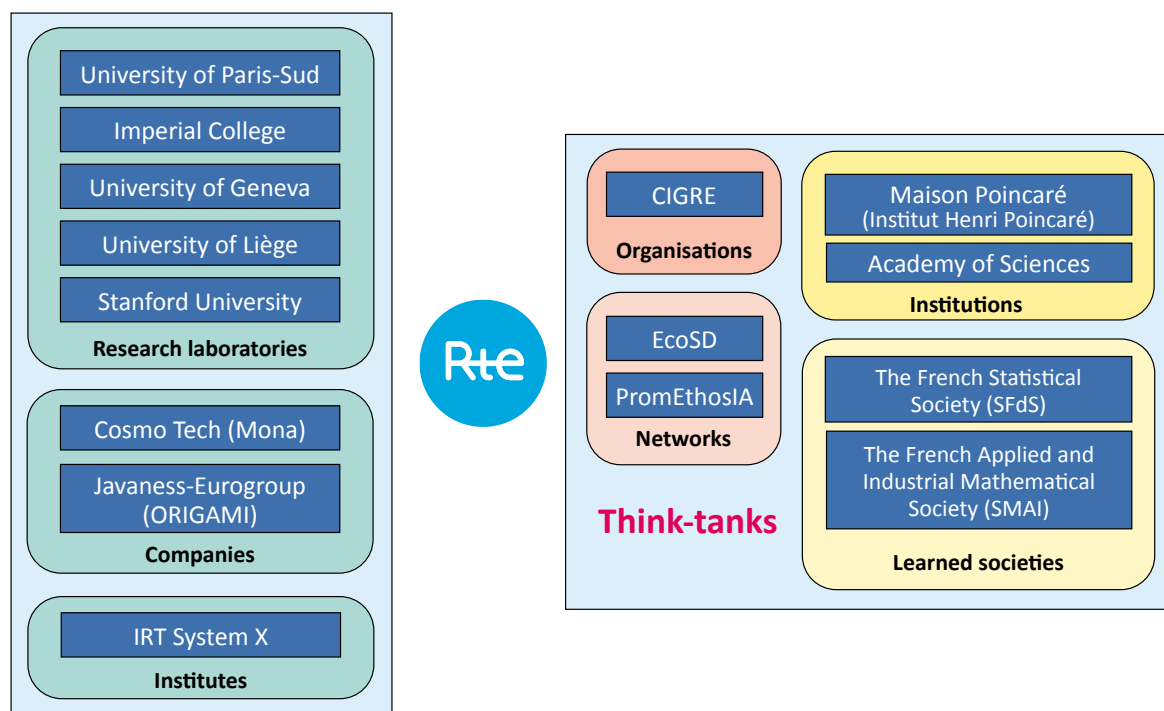
The specialisms are facing increasing complexity, and several “augmentation” initiatives are currently underway. Regarding the operation of the electricity system, AI algorithms for studies on operational

safety and for hypervision (the centralisation of monitoring tools) have already been developed by RTE (partly by means of theses and academic partnerships) and will be incorporated in future tools.

Bringing the network development studies to a successful conclusion will require simulating a multitude of situations, generating large volumes of data in terms of both space and time (the **imaGrid** project). RTE is using AI bricks, including neuron networks (the **ORIGAMI** project), to interpret the output of these simulations and capture their determinants. Prior to these simulations, the most plausible working assumptions must be defined and, to this end, an additional data acquisition module (internal document sources, online sources) has been developed using AI processing of natural language. This data extraction module should be easily transferable to the mid-term adequacy report and consultation studies.

AI - in the sense of data science and artificial intelligence – brings significant benefits to several areas of asset management, such as the detection

### MAIN RTE TIES IN RELATION TO DATA SCIENCE AND AI



of equipment defects. At the present time, a trial is underway to spot line defects using images taken by drones. For predictive maintenance, there is a wide choice of models for dealing with these issues, ranging from time-delay models to machine learning.

It should also be pointed out that a digital twin - a digital replica of the physical system - implemented for asset management, makes use of AI bricks to enhance the granularity of simulations.

In regard to maintenance, consideration should also be given to the automation of maintenance notifications and task scheduling (thanks to the concentration of data in operational centers). There are also potential applications in support functions: cybersecurity, assistance with budgetary trajectories for management control, summaries of audit documents...

### Technical and functional challenges

It is essential for RTE to pinpoint the requirements of the specialisms and examine the potential contribution of AI, but this process must ensure that AI solutions are adopted only when the hoped-for returns exceed those offered by other existing methods.

For all projects, it is also important to incorporate generic issues: causality, explainability, interpretability, robustness, machine learning bias, ethics.

There is a need to foster hybridisation of AI models and the knowledge and methods derived from the specialisms and from other disciplines: physics,

economics, etc. Multidisciplinarity is a key to success in many projects, along with stronger links with other areas of expertise (such as the existing links with meteorology and climatology).

Lastly, it is essential to work on employee acceptance of AI, and on maintaining and improving skills when dealing with ever more powerful decision-making tools that may cause apprehension.

### Data sharing and dissemination

AI requires a lot of data in order to extract information and thus improve the users' knowledge. It is therefore essential to have large volumes of good quality data, potentially (well) labelled. In practice, we are faced with restricted access to certain databases, input errors, etc.

Finally, it is important to prioritise open source solutions, which foster exchanges with external entities (AI world, other transmission system operators).

In order to accomplish its mission in the French electricity system, RTE must focus on how it can make best use in its decision-making tools of research in a variety of fields. AI offers many opportunities but requires also technical expertise derived most often from cross-cutting fields such as image and text processing.

By drawing on the French and international AI ecosystem, RTE is applying both theoretical knowledge and operational practices to the issues it must address.



### Further reading

- **The elements of statistical learning. Data mining, inference, and prediction**, T. Hastie, R. Tibshirani et J. Friedman - Springer (2<sup>nd</sup> édition, 2008)
- **Artificial intelligence**, S. Russel et P. Norvig - Pearson (3<sup>rd</sup> édition, 2010)
- **L'intelligence artificielle n'existe pas (Artificial intelligence does not exist)**, L. Julia - First (2019)

# ENERGY STORAGE: WHAT CONTRIBUTION CAN IT MAKE TO THE ENERGY TRANSITION?



**Claire LAJOIE-MAZENC** | Scientific Adviser

Energy storage has been sparking extraordinary interest for some years now, and in light of the variability of wind and solar electricity generation, is often perceived as the silver bullet for the energy transition. However, while there is little doubt that the availability of storage systems will provide significant flexibility in tomorrow's energy systems, their development is not straightforward.

For RTE, a proper understanding of the technologies that enable energy storage, and of their characteristics, is essential for knowing how to integrate them and to promote their use wherever they promise to be most advantageous for energy transition.

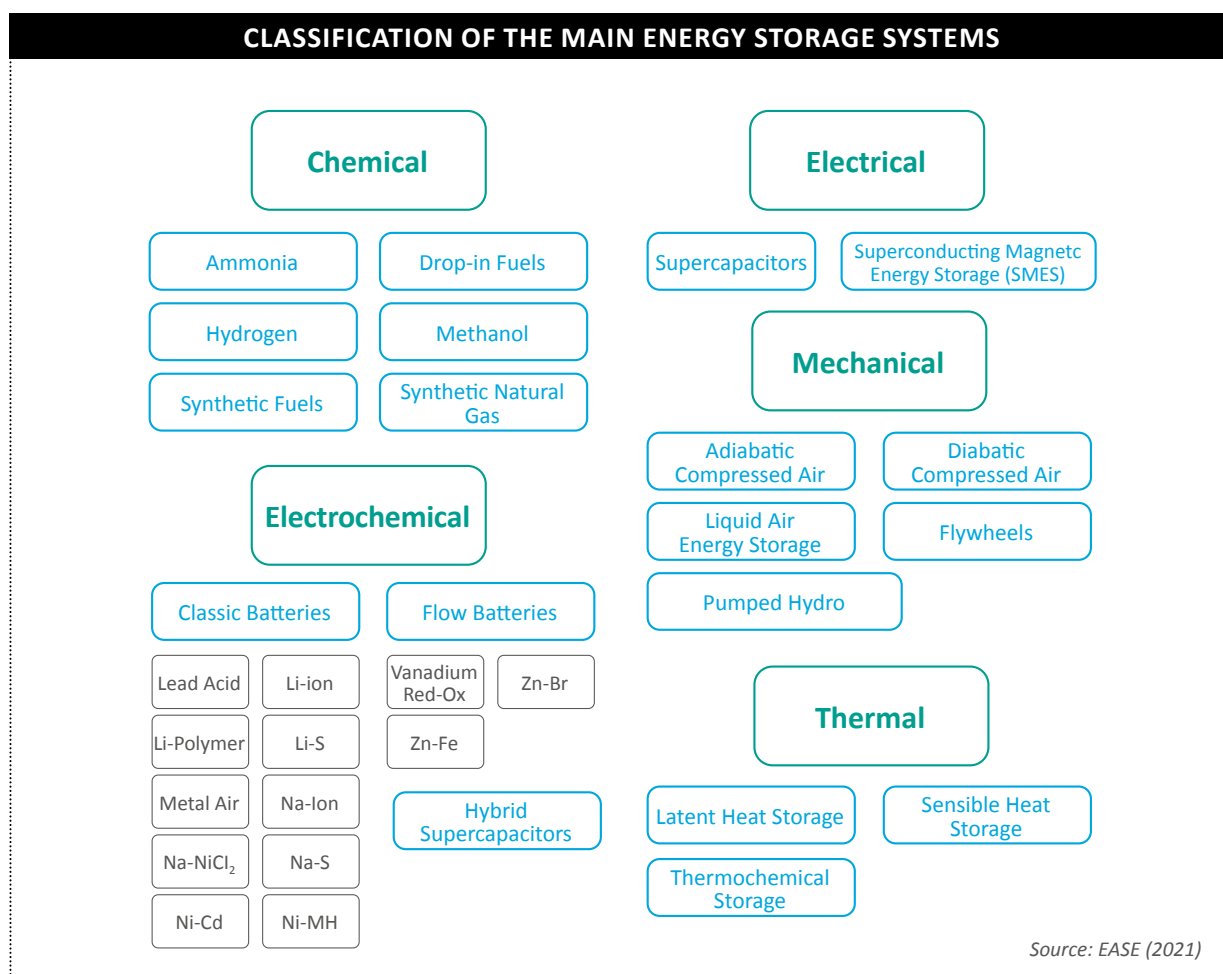


Though widely used, the word ‘storage’ includes many aspects that are not known or properly understood. Storage covers a very wide and everchanging range of technologies and services.

The two most prevalent storage technologies over the last few decades have been Pumped Hydro Energy Storage (PHES), representing around 200 GWh of capacity in France, and thermal storage. Thanks to flexible tariffs<sup>1</sup> for domestic hot water heaters, thermal storage remains the primary mechanism for daily flexibility in France.

But there is much discussion now about the development of a third technology: electrochemical battery storage, as a result of the impressive advances in lithium-ion technology (Li-ion).

All battery technologies are based on the reversible transfer of ions between two electrodes through an electrolyte and a separator. The technologies differ in the nature of their components. And this has a direct effect on their performance: the volumetric and gravimetric energy density, unit voltage, safety (risk of thermal runaway and flammability of organic electrolytes), as well as operating temperature, self-discharge rate, charge and discharge dynamics, and cyclability.



1. Programming of domestic hot water system operation in “off-peak” hours.

## Lithium ion, a versatile technology

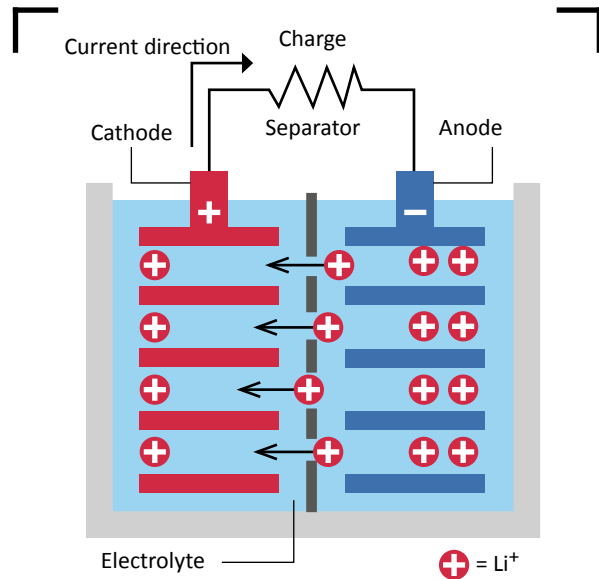
Today, the lithium-ion battery is the leading category of technology, owing to its performance, which makes it highly versatile. This versatility allows it to respond to a wide range of uses: from electric vehicles to domestic uses and stationary storage systems of all sizes, formed by simply combining the “basic building blocks”. There are possible combinations of cells<sup>2</sup> and modules (this includes the battery management system - BMS) to which can be added, depending on the application, more or less sophisticated converters, transformers, cooling systems, fire risk management systems, or energy management systems.

The volume and cost of these systems – in spite of falling markedly in the last 15 years – does limit their use to a few hours (1 to 6 hours at most, in practice). A common mistake is to “narrow down” the concept of a stationary storage system to just its electrochemical modules. In actual fact, the characteristics of the full system must be addressed: efficiency (of the order of 80% for a charge-discharge cycle, from the point of view of the electricity system), bulk, full cost (the modules amount to 30 to 45% of the full cost, depending on the connection level), etc.

## Stationary energy storage services

In the past, energy storage provided a means of smoothing out production needs. This reduced peak consumption and thus avoided the construction of additional plants and the use of energies with the highest carbon content. Postponing consumption to off-peak hours dispensed with the need to shut down nuclear units for a few hours, thereby saving on costly start-ups. These were systemic gains like supply-demand balance (SDB) services, delivered through arbitrage (provided by PHES) and the smart management of domestic demand (by means of the tariff-based control of domestic hot water).

The development of more modular storage systems with faster response times gave rise to new possibilities, in terms of both overall and local functions. Overall functions are possible whatever the storage location in the power system, as in the case of frequency regulation, for example. Local functions, such as managing congestion<sup>3</sup> or adjusting voltage, are necessarily localised.



> Operating principle of a lithium-ion battery

Most of the services provided by electrochemical storage are linked to intra-day flexibility. This covers the power requirements associated with system services, as well as the requirements for movement of energy to adjust solar production profiles (clustered around the middle of the day) to consumer needs (concentrated around early evening).

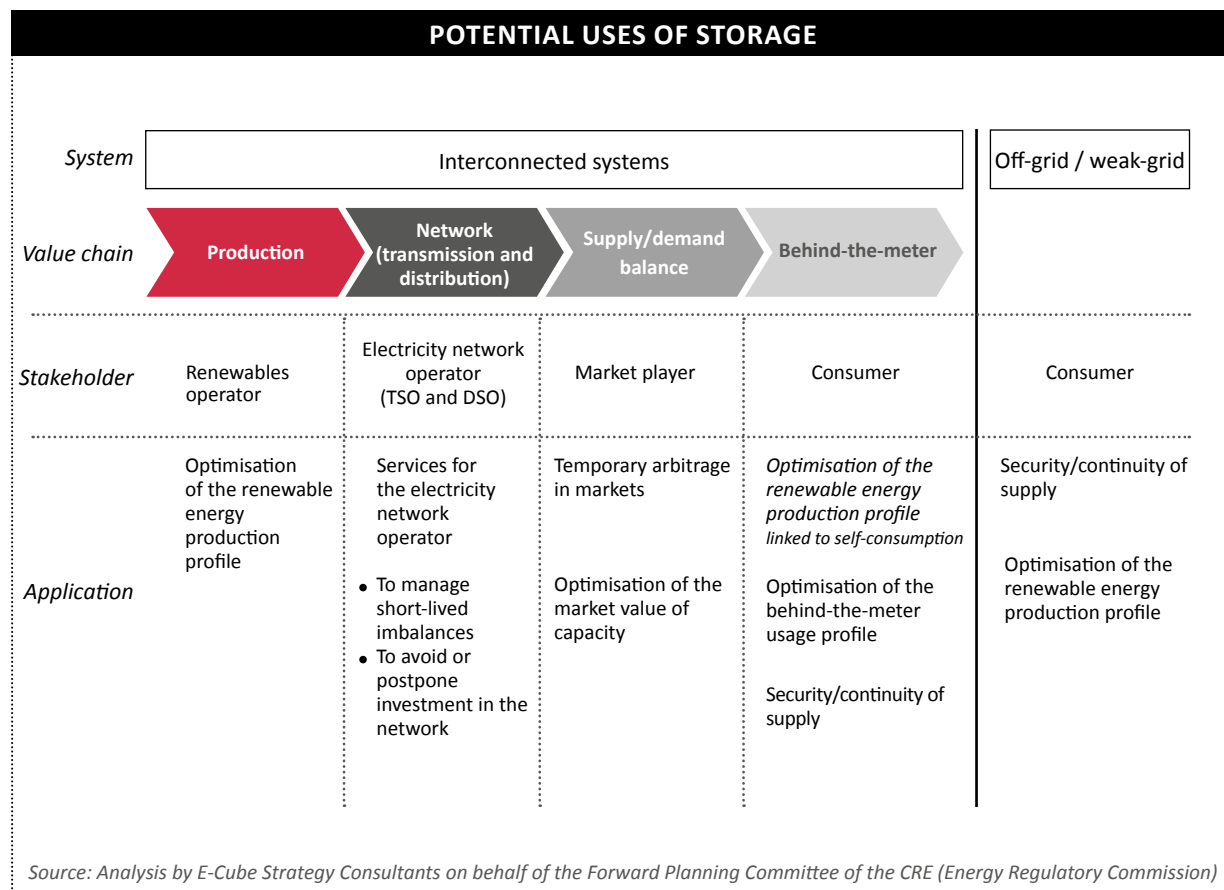
Predictably enough, studies<sup>4</sup> have shown that these requirements would be greater in scenarios involving a mass development in solar power generation. However, it is worth noting that these requirements can also be covered by other mechanisms (such as demand side management), and therefore that the actual development of these storage systems will be dependent on their competitiveness.

Furthermore, the development of renewable power generation, and the reduced share of dispatchable energy production, will bring about an increasing need for flexibility over longer periods of time: over months or over seasons, to compensate for variations in wind, or lack of wind, and low solar power generation in the winter. New solutions will then have to play a role, particularly through combinations of electricity/gas/heat energy carriers.

2. A cell is a stack of basic systems made up of electrodes/electrolyte, which, when connected to other cells fitted with a BMS, then constitute a module.

3. Congestion in electrical installations: overhead and underground systems are designed to be operated at maximum power. Peak shaving is required when energy flows exceed this value. Local storage prevents the loss of this energy, and enables its transmission – but for some losses – once the connection has the capacity again to transmit this energy.

4. Futurs énergétiques 2050 (Energy Pathways to 2050) (February 2022)



## THE VALUE AND DIFFICULTY OF MULTI-SERVICES

As the different individual services rarely generate enough revenue for an industrial storage installation, it is often necessary to achieve viability by combining several services. Although theoretically this is possible, in practice it creates real technical difficulties. In order to be able to provide a service at a given moment, the battery charge must be at a particular level, which will need to have been prepared in advance by appropriate charging or discharging.

In addition, multi-services raise contractual issues of principle, as it is essential to be able to plan ahead for, and manage, the priorities of these services, which can be mutually exclusive. For example, if an installation is being paid for congestion management but also wants to offer frequency regulation, what should be done if there is a conflict between these two services? Is it acceptable for frequency regulation to be put on hold occasionally?

It is important to be able to implement multi-services in order to offer an acceptable return on those storage installations that still cost a lot. But these multi-services must be closely scrutinised upstream, to anticipate all the situations in which they might be needed. It is also necessary to have assessed these situations against the electricity system's capacity to locally transmit the flows needed for charging and discharging, both to deliver these services and to prepare the battery to ensure its ability to deliver them.

## SAFETY: A MAJOR CHALLENGE

The safety of storage systems is and must remain a key issue. Given that the principle is to condense a maximum of energy into the smallest possible volume, any uncontrolled release of this energy produces significant risks.

Regarding batteries, Li-ion technology poses three risks:

- Thermal runaway, particularly if the charge is poorly controlled
- A major fire caused by an organic electrolyte
- An explosion linked to a release of gas during the degradation process

These risks must be correctly identified and managed through quality of manufacture and suitable management systems. Standardisation bodies are starting to take up the issue in response to more frequent fires and accidents worldwide.

## Reckoning with the environmental impact of storage

Energy storage is instrumental in supporting the development of non-dispatchable generating capacity, and creating real cross-sector coupling of the electricity, gas, or heat networks (whether reversible or not). This coupling accelerates the reduction in carbon intensity of energy based on the principle of “decarbonise all you can, convert the remainder”. Thus, the electrification of mobility - largely through batteries - is a “no-regrets solution” (at least in those countries with highly decarbonised electricity generation).

### Ensuring that the benefits outweigh the impacts

In terms of environmental impacts, the storage systems themselves have impacts due to the material used, the energy needed to manufacture them, and the losses associated with their operation. It is therefore essential to ensure that the benefits outweigh the impacts or, at a minimum, the impacts of alternative solutions, though this is rarely done. Regarding batteries, studies are underway however to gain a better understanding of these impacts, both in terms of the environmental footprint of the cells themselves or of the whole stationary systems.

Within RTE, the **RINGO**<sup>5</sup> project has conducted life cycle assessments early in the system design process in order to identify the major impacts and put forward modifications to the design with a view to reducing the environmental impact of

storage systems. These studies also provided an opportunity to establish that greenhouse gas emission during energy release was around 150 grams of CO<sub>2</sub>eq/kWh, that is to say, significantly less than the most carbon-intensive peak load generation (gas at 450 g, coal at around 1000 g) but more than the average French mix (approximately 50 g). This result, which may appear surprising, is attributable to the use of carbon-intensive energy for the extraction of resources and manufacture of modules and other system components, as well as to the losses arising during operation.

Furthermore, the studies carried out by RTE for the **Futurs Énergétiques 2050** report (Energy Pathways to 2050) have flagged up points to be watched for the procurement of mineral resources for the energy transition, and batteries in particular: lithium, cobalt and nickel but also copper, and to a lesser degree, aluminium.

This matter was very quickly taken up by the European Commission, with draft regulation aimed at “greening” the manufacture and end-of-life of batteries: thus, from 2030 onwards, batteries on the market will have to comply with minimum levels of recycled content<sup>6</sup>, with these levels increased from 2035. Though these requirements may still appear to be limited, they are however a rare example of environmental requirements going hand in hand with the development of a technology.

5. **RINGO** aims to test the use of a congestion management system based on a new two-level control system and three stationary storage systems.

6. 12% cobalt, 85% lead, 4% lithium, 4% nickel.

## **○ Understanding and incorporating storage for the energy and ecological transition**

The “Clean energy for all Europeans” package adopted in 2019 set out a definition of energy storage and strictly limited the possibility for players in the regulated sector to own and operate storage systems. Despite this, RTE has continued to show great interest in energy storage on several counts: regarding connection, integration in markets, the search for new opportunities, the testing of new solutions, as well as future-oriented studies.

What makes storage unusual is that it is both a consumer and a producer with, additionally, a limited stock of energy that can be combined or not with a client installation that is either a power producer or consumer. It has therefore been necessary to adjust the rules and requirements both for connection to electricity systems and for access to markets. Measures must be taken to ensure, on the one hand, that other network clients are not disrupted, and on the other, that the right capacity needed for system services is in place. To this end, studies have been performed at European and at French level.

### **Openings for new services**

Furthermore, the properties of battery systems (modularity, flexibility of location, reaction time of the order of milliseconds) raise the possibility of new services such as management of congestion or contribution to grid-forming (see the chapter on the dynamic operation of electricity networks).

New services are still to be thought out or tested, such as frequency support for on-the-hour transitions: when changes to generation plans in response to changes in market time slots produce significant frequency disturbances every hour. Finally, future-oriented studies that spotlight possible developments must include the new opportunities on offer, along with their technical, economic and environmental properties, as well as the impact of their development.

Today, the storage systems being considered are primarily Li-ion technology with battery durations of one hour (adapted to the system services) or 4 hours (for congestion or daily SDB).

By 2050, the technologies and their costs will have evolved, which will require regular monitoring so as to integrate these advances and new possibilities, particularly in medium-term (weekly) to long-term storage (monthly or seasonal). As of now, a great deal of research is being done on the development of so-called “solid-state” batteries that offer major improvements in safety. In contrast, changes in the cost of batteries, which is a critical parameter in a competitive environment, are unclear: even though many specialised firms are moving towards a steady decrease in these costs, resource pressures may also lead to stagnating or even rising costs.



## WHAT ABOUT ELECTRIC VEHICLES?

The electric vehicle is undoubtedly the best example of energy system decarbonisation through electrification. It establishes a new meshing of the mobility sector and electricity systems, and has therefore been the subject of forward-looking studies aimed at verifying the electricity system's capacity to support these new uses.

A study<sup>7</sup> carried out by RTE in 2019 stressed that there were no major issues, either in terms of energy needed (a few dozen TWh by 2035, in other words, one tenth of total consumption), or in terms of peak loads (around 6 GW), which can be absorbed as they are small compared to overall consumption.

The management of charging- including simple tariff mechanisms- makes it possible, by mitigating peaks, to achieve considerable savings (in the region of a billion euros a year) so reducing the need to turn to more carbon-intensive energies or to build peaking power plants.

This line of thinking has been extended even further: with the implementation of reversible connection systems, it is theoretically and technically possible to re-inject into the system (of a home, a building, or the general network) the electricity stored in a vehicle battery: this is the working principle of vehicle to home (V2H), vehicle to building (V2B) and vehicle to grid (V2G). These features would double the energy being carried, but they have far less value. In addition, this does not factor in the constraints and misgivings of the users of these vehicles, which would then be operated as domestic storage, with the premature wear-and-tear that this may cause for the vehicle battery and, most of all, with the environmental impact of the additional devices needed to deliver this reversibility.

Furthermore, RTE's study of integration, which focuses on issues of supply-and-demand balance, was supported by an Enedis- RTE<sup>8</sup> joint study on the infrastructure requirements of electricity networks and charging systems associated with long-distance motorway mobility. This study confirmed the encouraging view that investment needs will be significant but manageable, though with peaks of 40 MW across 200 charging stations by 2035 in the highest projections for the busiest motorway service areas. However, developments in the technologies and increased power ratings will also need monitoring, with a view to reducing charge times (assumed to be 30 minutes).



### Further reading

- **Stockage électrochimique : revue des technologies émergentes (Electrochemical storage: an analysis of emerging technologies)** - Revue de l'Électricité et de l'Électronique (Electricity and Electronics Journal) (2018)
- **Empreinte environnementale des batteries insérées dans un système électrique mature (Environmental footprint of battery integration in a mature electricity system)** - Revue de l'Électricité et de l'Électronique (Electricity and Electronics Journal) (2018)
- **Batteries Europe, Strategic research agenda for batteries** - European Commission, European Technology and Innovation Platform on Batteries (2020)
- **Energy storage applications summary, Report** - EASE (2020)
- **Smart Sector Integration, towards an EU System of Systems, Position Paper** - European Technology and Innovation Platform Smart Network for Energy Transition (2021)
- **Study on energy storage - Contribution to the security of the electricity supply in Europe** - European Commission (2020)

7. *Enjeux du développement de l'électromobilité pour le système électrique (Electromobility development challenges for the electricity system)* (May 2019).

8. *Les besoins électriques de la mobilité longue distance sur autoroute (Electricity requirements for long-distance motorway mobility)* (July 2021).

# THE ECONOMICS OF ENERGY SYSTEMS: TOWARDS A SYSTEMIC VIEW

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**Marc LE DU** |

Distinguished Expert,  
Economics of Energy Systems

The French electricity system is part of a bigger system, in terms of geography, as it is interconnected with neighbouring countries, but also increasingly in terms of its interactions with other energy systems: gas, hydrogen, heat, etc.

In order to gain insight into the future of the electricity system, it is necessary to place it in the context of a wider energy system, and to understand how the different energy carriers will interact at the European level. These insights will allow RTE to anticipate its requirements, both for the management of its infrastructure and for its role in balancing the power system.

The economics of energy systems offers a systemic view that goes beyond monetary and financial aspects. It looks into environmental impacts and social issues so as to transcend “traditional” value and bring out all decision-making indicators.

Etymologically, the term economics refers to “household management”. As applied to individuals, the term encompasses both the behaviour leading to restricted spending and the savings induced by this behaviour. The ordinary meaning of the term covers all the activities performed by a community in relation to the production, distribution and consumption of goods and services<sup>1</sup>. There are nearly as many branches of economics as there are goods and services: cultural economics, industrial economics, agricultural economics, etc. However, this collective sense of economics shares with its individual meaning the idea of optimisation, of rationality in the use of resources that will make it possible to obtain the desired goods and services.

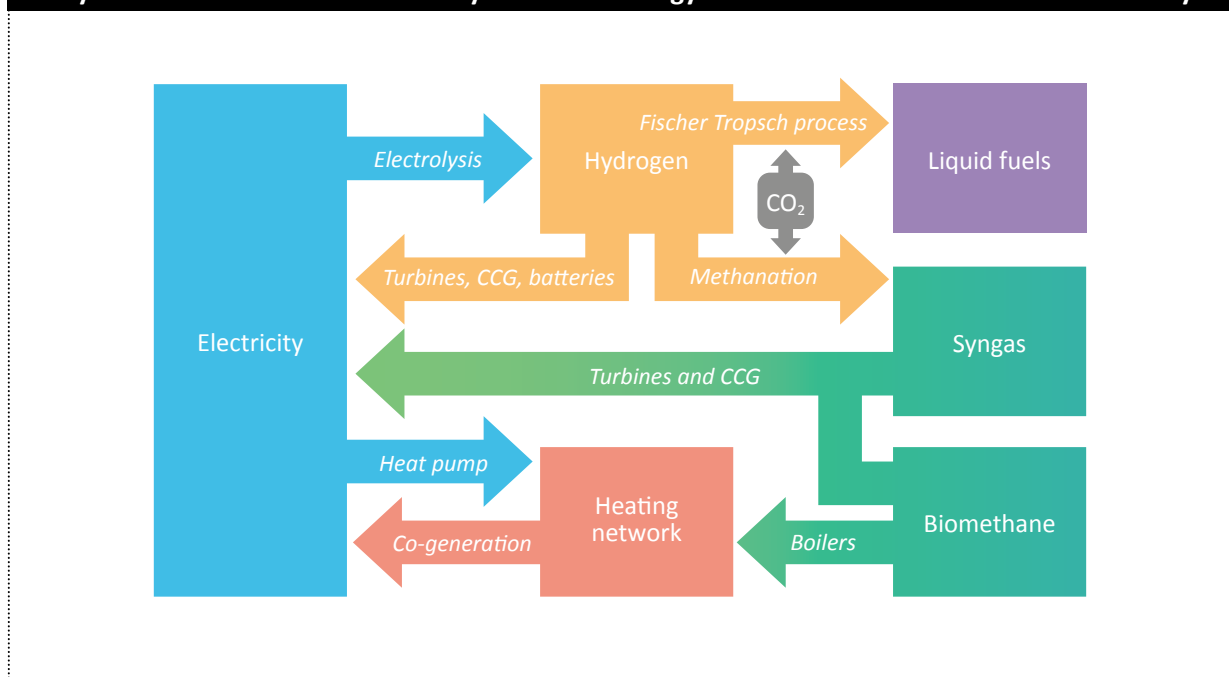
In other words, the economics of energy systems deals with the “rational” organisation established to deliver an energy service. From the point of view of the electricity system, this covers the traditional power supply chain: production, transmission,

distribution and consumption, to which can be added the energy storage and flexibilities that are under development.

But a number of different elements need to be taken into consideration. The definition of economics includes the stage of consumption of the activity, in other words, energy uses. They are at the forefront of the key elements in developments in energy systems: switches in carriers (to move away from fossil fuels, for example), resource efficiency, energy efficiency, and consumption flexibility.

Economics also grapples with the organisation of the system (community activities) and not just with the “how much does it cost”. The aim is therefore not just to reduce economics to euros, even though the quest for minimum cost or maximum profit is often at the heart of the activity. Other constraints (social, environmental, societal) weigh heavily on the system, and should be factored into the analyses<sup>2</sup>.

#### Key interactions between electricity and other energy carriers on the road to carbon neutrality



1. In some definitions, the term “goods and services” is replaced by “wealth”.

2. Moreover, the usual equation of “economics = euros” often leads to monetising the constraint, for example by allocating a cost or a price to a tonne of CO<sub>2</sub>, to a MWh of “failure”, etc.

Even if the only purpose was to know “how much it costs”, it would be necessary to know “how it works”.

Finally, although the economics of the electricity system can be analysed in isolation, extending the scope to include energy systems seems necessary given the prospects of links between systems (hydrogen and synthetic fuels using the electricity system, the possible need for power system flexibilities because of other energy carriers). At this stage, these prospects are speculative, but it is by carrying out an economic analysis of these prospects (which is to say, of the organisations that they involve) that a critical judgment can be made on their practicality.

### The importance of political decisions in energy system developments

The economics of energy systems in France cannot depart from the framework established by energy policies. For the electricity and gas sectors, a distinction must be made between the era of the large state monopolies EDF and GDF, the era of European liberalisation of energy markets (in the early 2000s), and the era of necessary energy transition that is before us now.

The era of monopolies bore the stamp of Marcel Boiteux<sup>3</sup>. He implemented the principles of electricity pricing, designed to encourage rational choices in investment decisions. This policy was based primarily on selling at marginal cost, discounting, and maximisation of profits. Investment decisions

over this period were also driven by a political commitment to developing a French fleet of nuclear power plants (through the Messmer Plan, launched in 1974).

The era of energy market liberalisation gave rise to a fundamental change in the organisation of the gas and electricity sectors, led by Europe, which was keen to expand the common market to include energy, even if it could not intervene on the electricity production side of national energy policies. In particular, this period saw the operational network of the generating fleet expand beyond national borders, thanks to the capacities of interconnected systems. This was also the period during which the combined cycle gas turbine (CCGT) power plant emerged as a leading production technology.

Lastly, this period saw developments in wind and solar renewable energies, digital technology, electric vehicles, and batteries. Prospects for new power sources, new electricity uses, new needs, and new flexibilities.

The period now beginning is characterised by climate change and the necessary energy transition, within the framework of “climate-energy” policies designed to reduce our greenhouse gas emissions or even make them carbon neutral. These carbon-neutral strategies require energy planning up to 2050, or give rise to severe constraints placed on the system. Over and above the impact on climate, these policies also call into question the environmental and societal footprint associated with energy systems.

## ○ The French and European policies on carbon neutrality

In France, the National Low Carbon Strategy (SNBC)<sup>4</sup> is based on two cornerstones. The first is a roughly 50% reduction in French energy consumption, which is expected to drop from about 1,800 TWh/year to approximately 900 TWh/year (across all energy sources) as a result of energy savings and energy efficiency measures. The second cornerstone is the

delivery of a national energy balance that is carbon neutral overall: end-point consumption must be supplied from national production.

This second cornerstone has great structural importance as it requires a substantial reduction in the share of gaseous fuels (natural gas) and liquid

<sup>3</sup>. CEO of EDF (1967-1978) and then Chairman of EDF's Executive Board (1979-1987).

<sup>4</sup>. The National Low Carbon Strategy is one of the components of the Climate-Air-Energy Plan, which is France's roadmap for combatting and adapting to climate change.

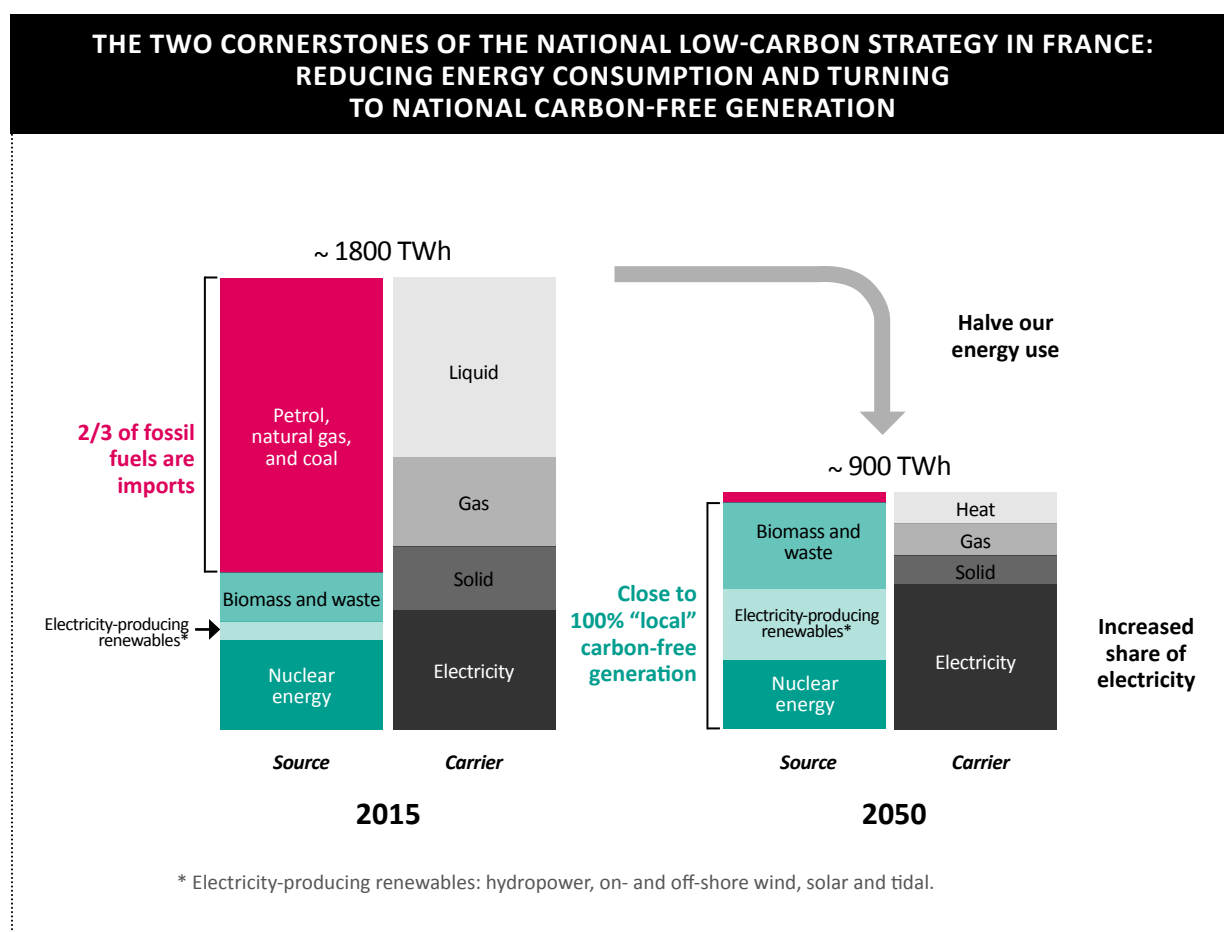
fuels (oil). Electricity is the only energy carrier that is growing due to the switches in energy carriers for transport, heating, and industry. The National Low Carbon Strategy however does not stipulate the respective shares of nuclear and renewable energy in generating electricity. It also makes no reference to the exchanges between France and its European neighbours, and does not address balancing issues (which are increasing with the use of non-dispatchable renewable energies).

### Broader options at the European level

The European Commission also sets its own carbon-neutral objectives. They involve a reduction in energy usage but leave several options open for different combinations of energy efficiency, energy savings, and choice of energy carriers. They include,

in particular, the possibility of carbon capture and storage, an option that was excluded by France but is favoured by other European countries. There is also more room for synthetic e-fuels (hydrogen, methane, methanol), leading to less direct electrification than with the National Low Carbon Strategy, but rather to more “indirect” electrification.

These strategies allow gas companies to keep their energy carrier. But this carrier must derive from low-carbon energy sources. Furthermore, the European Commission has called upon the two ENTSOs - electricity and gas - to devise joint scenarios for the development of the transmission systems for their two energy carriers, verifying at the same time that the carbon-neutral targets can really be achieved.





## ○ Promoting RTE's system-wide approach

The economic analysis of energy systems can feed into RTE's industrial policy in its two key roles.

### The role of system infrastructure operator

The aim for RTE is to plan for possible future developments in electricity production on the one hand, and electricity uses on the other. These two areas of focus inform the decision to develop (or not) the power networks.

For example, the development of a hydrogen sector depends on the economics of the energy system (under the climate constraint). The size of this sector may make it essential to develop networks to supply the electrolyzers, depending on their locations

Conversely, taking into account the possibilities and constraints of the networks makes it possible to vary, in economic analyses, the importance to the electricity system of the developments being considered. In the past, the relatively low costs of the large transmission networks meant that they had only a minor influence on the optimisation of the production-transmission system, the costs of which were dominated by production. Today, the changes to the energy system could call this into question: the connection of power generation at lower voltage levels (high voltage HTB1), new grid technologies (underground HVDC), the connection of offshore energy (in the region of one billion euros per GW).

### The role of electricity system operator

The balance in the electricity system, of which RTE is the guarantor in France, is dependent in particular on the development of one form or another of electricity generation, and on consumption flexibilities. The point is to ensure that the balance can be maintained, to determine the conditions for the potential development of additional sources of flexibility. This requires a relatively detailed definition of the ways production and consumption work in France as well as in Europe.

In more integrated energy systems, the combination of energy carriers can contribute positively to overall operation. The aim, for example, is to avoid producing syngas using electricity, if electricity is being produced from this same syngas. Given the

yields for conversion in one direction (power-to-gas: about 70%) and another (gas-to-power: about 50%), simultaneous operation would destroy energy. The need for dispatchable production methods and the increasing interaction between energy carriers also require the comprehensive management of electricity and gas storage, a strategy for which will need to be found.

Lastly, economic studies challenge and feed into the analyses of electricity system regulation: which signals ensure that the different stakeholders of the system are properly coordinated? What are the models of payment mechanisms for the stakeholders? How will price signals develop? Etc.

### Promoting a system-wide analysis, and extending it to the energy system

One of RTE's strengths is its system-wide approach, which few stakeholders have. Many of them base their economic analyses on the levelized cost of energy, giving the "energy" value needed to cover the production costs of a given technology. This type of indicator does not reflect the implications of developing this technology in a complete system, the pooling with and the multiplexing gains from other elements in the system, the flexibilities, and the networks required. However, these aspects are covered by the economic analyses carried out by RTE, for example in the **Futurs Énergétiques 2050** report (Energy Pathways to 2050). This study puts forward "systemic" indicators that take into account all the components of the electricity system, and characterises them by their costs (gross investment costs, annualised total costs factoring in the return on capital) and their technical, environmental, and societal implications.

The energy transition calls for a reassessment of the place of different energy carriers, by way of switches to electricity (electric vehicles, heat pumps, electrification of industrial processes) or other solutions offering access to low-carbon energy sources (synthetic gas or liquid fuels, biomass). All the more so as some energy carriers constitute indirect electrification, in particular through hydrogen production by electrolysis. With time, dispatchable energy sources supporting the balancing of the electricity system will also come under review (hydrogen or syngas or biogas turbines, etc.). This supports an extension of the "systemic" vision to

all energies, while keeping in mind that the aim is to better understand the place of the electricity system in the energy mix.

The first step is to analyse the “useful energies”, which correspond to the different energy uses, as a starting point for various studies, and which detail the services provided by each energy use (for example, the number of passenger-kilometres). This provides a link with the measures aimed at societal behaviours (energy savings, for example). Building on these “useful energies”, the next step is to work back to the final energies, depending on the energy carriers, right back to the production sources.

### Tools and data for the effective simulation of the energy system

A systemic analysis is only possible if the operation of the system being analysed is correctly represented (see box). At least two conditions appear to be necessary. It is critical to have the right analytic tools, and simulation tools especially. And it is also important to have high-quality input scenarios, particularly for the descriptions of the hazards that may affect system balance, many of which are dependent on the weather and on the hour-by-hour demand for electricity as shown by load curves.

The desire to extend the present electricity system analyses performed with **ANTARES** to the whole energy system may seem unrealistic or even pointless. Unrealistic because of the amount of effort needed to obtain the same level of accuracy for all the energy carriers as currently achieved for the electricity system. Pointless because it would not be justifiable for RTE to do so for the whole energy system. In effect, the level of accuracy that is required must be measured in light of the objectives of the analyses, which are limited to the issues affecting RTE. In other words, it means finding a level of accuracy that is “necessary and sufficient” for understanding the implications for RTE’s activities.

### Linking up economics, environment, and societal dynamics

The economics of energy systems is not simply a matter of monetary value. Along with defining the system in terms of euros, it is also about defining its environmental and social impact.

This approach is similar to the one used in life cycle assessments in environmental analyses. Work has begun in fact to deliver a sufficiently detailed definition of the components of energy systems, to feed into three strands: costs, environment, and societal dynamics. In the economic strand, this life cycle assessment must include the financing of the systems, which represents an important part of the costs. For the societal dynamics strand, the aim is to introduce a quantitative aspect into the analyses - the jobs associated with the systems - and a more qualitative aspect: the societal dynamics influencing their acceptability.

### Developing a multicriteria analysis of systems “on an uncertain trajectory”

One of the main criticisms of system cost optimisation tools is that they are based entirely on future projections, the result thus being highly sensitive to necessarily uncertain assumptions about the long-term prospects: changes in the costs of solar power, growth in consumption, etc. The past – and even the recent past – suggests the need for prudence in the use of such methods, and prompts the development of analyses that factor in the expected (or possible) uncertainty of development scenarios. This will make it possible to take account of the “stranded costs”<sup>5</sup> associated with one investment strategy, or an “option value” associated with another. Other research work is now looking at optimisation in an uncertain future, outlining all the possible futures in the light of hazards.

As an alternative, another approach has been put forward, based not on optimisation but on the conversion of development assumptions into relevant indicators, making it possible to characterise the scenarios according to the area of focus of the analysis (economic, environmental, societal), or to measure a system’s resilience to highly adverse conditions. The aim is to use these analyses to guide the political decisions that have to be made.

### Building targeted partnerships but keeping RTE’s role as lead contractor

This is a broad subject, of great interest to many. RTE cannot by itself have a complete picture of the whole energy system in all its forms, and must therefore build partnerships that allow it to advance its aspirations. However, these partnerships must

<sup>5</sup>. Costs above those initially planned, owing to a shorter operating life than first anticipated.

take into consideration the potential sensitivity of the results of economic analyses, which are often used to promote the visions of the stakeholders and the interests of the sectors.

At the initial stage, the preferred partnership-based approach could involve “supply” partnerships, probably in the form of bilateral agreements (with a specialist in one technology for example). This type of partnership can help enhance the quality of the “building blocks” of analyses, while keeping in-house the “system” assembly know-how. Academic partnerships are also useful for fostering improvements to methods and tools in particular.

Finally, more collaborative partnerships can also be considered. These were used in the past, with GRTgaz for example, in order to carry out joint modelling of electricity and gas systems. These types of partnerships are an effective response to the fact that RTE cannot single-handedly drive a vision of the whole energy system. They also pave the way for a European dimension that takes better account of the physical interconnection of all the energy systems.

## TWO MAIN TYPES OF ENERGY SYSTEM MODEL

Two main types of model are used to underpin the economic analyses:

- **Energy balance models:**

These models “optimise” the energy systems in order to arrive at least-cost solutions under different constraints (the CO<sub>2</sub> emission trajectory, for example). There are several models, including PRIMES and MARKAL-TIMES. These models have their limitations, such as working with annual energy (when in fact hourly intervals are required in order to represent the balancing of the electricity system). These models are not yet used at RTE.

- **Models simulating the operation of the electricity or even of the energy system:**

These models simulate the operation of the electricity system, for a given generating fleet. In particular, they can focus on the representation of the hazards impacting the energy system. They rely on optimising variable operating costs. RTE has developed and deployed the **ANTARES** model for the analysis of the supply-demand balance and for the development of large transmission networks. Work has been carried out in the last few years to incorporate into it energy carriers other than electricity: gas, hydrogen, etc.



### Further reading

- **Futurs Energétiques 2050: les scénarios de mix de production à l'étude permettant d'atteindre la neutralité carbone à l'horizon 2050** (Energy Pathways to 2050: production mix scenarios under review for carbon neutrality by 2050), RTE (2022)
- **Stratégie Nationale Bas-Carbone (SNBC)**, (National Low Carbon Strategy), Ministry of Solidarity and Ecological Transition (regularly updated versions)
- **The European Commission Climate Strategies and Targets, and The 2050 Long-Term Strategy**, European Commission website
- **Yearly publications by the International Energy Agency (IEA):** World Energy Outlook (WEO) for an overview of energy around the world, and Energy Technology Perspectives (ETP) for the energy performance and costs of key technologies



# ELECTROMAGNETIC FIELDS AND THE PRECAUTIONARY PRINCIPLE



**François DESCHAMPS**

Distinguished Expert,  
Electric and Magnetic Fields

The 50 Hz electromagnetic environment is well known and well controlled. The question of potential adverse health effects of exposure to electromagnetic fields (EMFs) has been under review for 40 years and has produced a considerable body of scientific research. Research has not been able to produce any evidence of an impact on human health. Despite compliance with regulations and continuing lack of proof, EMFs remain a cause of public concern. To address this concern, RTE has to implement a policy of responsible management of this issue. This entails applying the precautionary principle, which allows the company to deal serenely with this matter and to ensure that the management of the electricity system provides the best possible guarantee for the protection of the health of local residents and of employees.

The sources of 50 Hz electric and magnetic fields<sup>1</sup> are well known: anything that generates, transmits, distributes, uses and transforms electricity is a source of extremely low frequency<sup>2</sup> electromagnetic fields (ELF-EMFs). However, it is simplistic to talk about ELF-EMFs in general because ELF electric and magnetic fields are independent, so that there are in fact two distinct environments: the relatively simple electric environment, and the infinitely complex magnetic environment.

The 50 Hz electric environment is simple because there are few sources of 50 Hz electric fields (50 Hz EF). The magnitude of the emitted field is directly proportional to the voltage, and sources of high 50 Hz EFs will therefore consist of high or very-high voltage equipment, that is to say, the 225 and 400 kV networks in France. Nevertheless, this electric field is easily shielded by most materials, even poor electrical conductors like building materials and vegetation. In addition, underground power networks do not emit 50 Hz EFs. As a result, high magnitudes of 50 Hz EFs are only found in open space in the vicinity of high-voltage overhead power lines. Only low voltage ranges, and therefore weak 50 Hz EFs, can be found in non-residential and residential settings.

The 50 Hz magnetic environment is complex because there are countless sources of 50 Hz magnetic fields (50 Hz MF). Without even taking into account the electricity networks, our residential environment includes several dozen sources of 50 Hz MF: every electrical appliance is a source of 50 Hz MFs.

Furthermore, we can get very close to many of these sources, so that the 50 Hz MFs emitted by domestic sources are often, in a limited area, much higher than those of electricity networks. It is not uncommon to measure several hundreds of  $\mu\text{T}$  in touch with household appliances. However, they weaken very rapidly, in inverse proportion to the cube of the distance, so the magnetic field strength decreases by a factor of 1,000 as one moves from 5 to 50 cm away. They quickly become negligible, and this will almost always be the case at a distance of 1 metre from any household appliance.

The emission from each of these sources can be assessed: it simply involves making measurements. But their wide variability means that it is not possible to assess a generic emission level: two electric shavers

can emit very different fields. The only exception is that of sources that have a simple geometry and are technically very standardised, such as electricity networks.

### Measurements and interpretations

It is possible to measure 50 Hz electric and magnetic fields but there are marked differences between the two. The measurement of a 50 Hz electric field is difficult as almost all materials can disturb the field. Thus, a 50 Hz EF meter sensor will be disturbed by all the objects surrounding it, including the operator performing the measurements, and even the weather conditions: 50 Hz EFs cannot be accurately measured in humid conditions. Measuring 50 Hz EFs therefore requires sophisticated instrumentation and well-trained professionals.

If measurement is difficult, in contrast the interpretation of 50 Hz EFs is simple as there are few significant sources: if a 50 Hz EFs measurement exceeds a hundred volts a metre, then the measurement location is an open space in the vicinity of a high-voltage overhead line.

Measuring the 50 Hz magnetic field is straightforward as practically nothing disrupts it. So unlike the 50 Hz EF, accurate measurements of 50 Hz MFs are possible with a handheld instrument. It does not require a sophisticated device or professional training.

However, interpreting the 50 Hz MF measurements can be tricky owing to the numerous sources. For example, in a dense urban area, a measurement close to a high-voltage underground cable can be biased by power distribution networks, street lighting, electrified public transport, devices running in nearby buildings, etc. The difficulty stems from the number of field sources, but also from the fact

1. What is said here for the 50 Hz frequency also applies to 60 Hz, the other operating frequency of electricity networks. 50 Hz is the European standard.

2. ELFs range from 0 to 300 Hz and therefore cover the operating frequencies of electricity networks, 50 and 60 Hz, as well as their first harmonics.



that many of them may be hidden.

### The indirect effects of 50 Hz EMFs

Electric and magnetic fields at 50 Hz produce several indirect effects. The first is of critical importance for the safety of network workers: induction phenomena, which are likely to produce high (and therefore dangerous) voltages wherever there are long, parallel electric lines. This is a known mechanism and RTE's maintenance workers are trained to manage this security issue.

These effects are also responsible (to a lesser degree) for stray voltages and currents in metallic structures near electrical installations. In the case of agricultural buildings, the length of metallic structures is limited and the phenomena are not dangerous. Nevertheless, they do have disruptive

effects and can cause stress to livestock, which can affect its productivity. These stray phenomena can be diagnosed and cancelled out through equipotential bonding and earthing of all metallic structures.

The corona effect is an indirect effect of a strong electric field on the surface of transmission line conductors. It is mainly perceived by the "corona noise", the characteristic crackling and hissing sound associated with very high voltage power lines. The corona effect also generates radio-electrical interference, primarily in the 150 kHz to 30 MHz frequency range. Therefore, only the long-wave radio band may be disrupted. Finally, the corona effect is likely to create localised ionisation of molecules in the air, and thus chemical reactions. The best-known of these reactions (though small overall) is the ozone creation by overhead lines.

## PROPERTIES OF ELECTRIC AND MAGNETIC FIELDS AT 50 HZ

	ELECTRIC FIELD	MAGNETIC FIELD
Interaction with the environment	<b>Strong</b> <i>(field easily disrupted)</i>	<b>Weak</b> <i>(field not easily disrupted)</i>
Reduction of fields	<b>Easy</b>	<b>Difficult</b>
Measurement	<b>Difficult</b> <i>(many risks of error)</i>	<b>Easy</b> <i>(little risk of error)</i>
Interpretation of measurement	<b>Easy</b> <i>(few field sources)</i>	<b>Complex</b> <i>(multiple field sources)</i>

## OCCUPATIONAL EXPOSURE TO ELF-EMFS

Some work positions in the company entail high levels of exposure<sup>3</sup> that might produce immediate biological effects<sup>4</sup>. French regulations, based on a European directive, were introduced in 2016 to protect workers from these effects. However, due to the potential impact of these regulations on some core activities, live-line working in particular, RTE had taken early action and pre-emptively implemented them at the end of the 2000s.

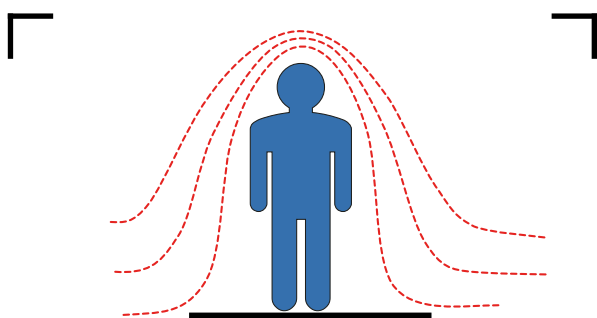
3. The order of magnitude here is millitesla, in other words, 1,000 times higher than the order of magnitude for residential environments, where exposures are measured in terms of microtesla.

4. With low frequencies, these immediate effects consist of a stimulation of muscle and nerve tissue. At high frequencies, there are thermal effects.

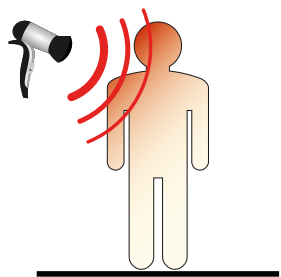
## ○ Humans and the ELF electromagnetic environment

Once again, there is a sharp contrast between electric and magnetic fields.

The electric field reacts strongly with the environment and therefore with the human body. At low frequencies, the human body behaves much like a Faraday cage and totally distorts the electric field. The field within the body is significantly weaker (by a factor in the order of 100,000) than the external field. The exposure of the body is therefore always an overall exposure.



> The human body interacts strongly with the electric field



> The human body does not distort the magnetic field

Conversely, the interaction with a magnetic field is very weak, and the human body does not produce any distortion of the external magnetic field. As a result, the concept of exposure can be difficult to define. For example, for someone using a hair dryer, the hand holding the dryer is at 100  $\mu\text{T}$ , the head on the side being blown with hot air is at 1  $\mu\text{T}$ , while the other side of the head will be at 0.1  $\mu\text{T}$  (these figures are only indicative). In this type of example, it is therefore difficult to quantify the exposure of a person using a hair dryer.

Only the relatively homogeneous magnetic fields (on the scale of a human body) can be easily transposed in terms of body exposure. This type of homogeneous field can only be generated by large-scale sources such as high-voltage overhead lines. Having a good understanding of the 50 Hz MFs generated by the power networks can therefore help assess the residential exposure of locals.

### Decades of research on the biological effects

There is extensive scientific literature on the question of the effects of EMFs on human beings. For high and low frequencies combined, 10 years ago the WHO website identified more than 25,000 scientific publications, making EMFs one of the environmental factors that is most studied around the world, far more than asbestos, lead or tobacco.

The first records of “electrophysiology” experiments date back to the end of the 19<sup>th</sup> century, in particular those of the Frenchman d’Arsonval. But doubts about health effects actually only really go back to the 1960s. At that time, questions were raised about the links between electric fields and non-specific symptoms (loss of libido, stress, insomnia, etc.) reported in some Russian high-voltage substation workers.

This period also saw the development of large networks at 400 kV and above. The unpleasant indirect effects of strong electric fields (spark discharges) increased, and were much more experienced by electricity industry workers. The question of the possible long-term effects of exposure to electric fields was therefore justified, and has been extensively covered in scientific publications. CIGRÉ took up the issue and published a first technical booklet on electric and magnetic fields in 1980 (CIGRÉ TB 021), a few pages of which were dedicated to the possible adverse health effects of electric fields.

But concerns about electric fields died out in the 1980s, firstly because the Russian observations had not been confirmed anywhere else, and secondly because magnetic fields rapidly became the topic of scientific and media focus.

This research stemmed from the 1979 publication of an epidemiological study which observed a link

between childhood cancers (leukaemia and brain cancers) and electricity systems. Since electric fields do not penetrate houses, and since studies in the 1960s and 1970s did not flag up any suspected carcinogenicity, magnetic fields were deemed to be the possible mechanism that could explain the link that had been observed.

This was followed by 40 years of research, with dozens of epidemiological studies. Several of these confirmed a link with childhood leukaemia. However, these studies were all undermined by the same weakness: the evaluation of exposure. Although the residential exposure in the vicinity of overhead power networks can be assessed, none of the other sources are considered. The evaluation of exposure is therefore systematically biased.

For all the other studied diseases, including brain cancer in children and all adult cancers, no recurrent link emerged. Consequently, there is now practically no active research on these topics.

Along the same period, hundreds of experimental studies were carried out. The overall results were negative: the experimental studies failed to identify a biological mechanism of action from 50 Hz MFs that would help explain or substantiate the link with childhood leukaemia observed in epidemiological studies.

However, an important milestone was reached in the early 2000s, when magnetic fields were classified in group 2B, “possible carcinogens”, in response to what was considered to be a limited evidence of a link with childhood leukaemia. There is deemed to be insufficient evidence for all the other diseases that were studied, particularly other cancers in children, and cancers and leukaemia in adults, and regarding these diseases EMFs are therefore classified in group 3, “not classifiable”.

At the present time, after 40 years of research, the state of the art is a remaining doubt from the epidemiology, and the persistent absence of any evidence from experimental studies. The health risk, if any, is low and limited: the extensive epidemiological study **GEOCAP** showed that in France less than one case per year could be attributed to EMFs generated by HV lines.

## THE VARIOUS TYPES OF SCIENTIFIC STUDIES

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Studies on EMFs and health can be classified into two main categories: experimental studies and epidemiological studies. Experimental studies aim either to reproduce human diseases in animal models, or to identify EMF mechanisms of action in living organisms. These studies are referred to as “provocation” studies: cells or animals are intentionally exposed, in a bid to produce observable effects.

Epidemiological studies do not interfere in the course of events, they are “observation” studies. They are designed to reveal correlations between diseases and lifestyle factors (such as eating habits) or the environment (such as exposure to EMFs). The strength of such studies is the fact that they involve humans, but their weakness is that they take place in an inherently multifactorial environment in which it is extremely difficult to isolate weak effects, and all the more so for rare diseases.

## ○ RTE and the research

RTE is co-funding research projects focused on the thresholds for direct or indirect effects from EMFs, on humans (Montpellier University and the London Health Research Institute - LHRI), on animals (experimental farm, marine fauna), or on devices (disruptions to medical implants).

The joint study by Montpellier University and the Canadian LHRI involves exposing human volunteers to high MF values (of up to 50,000  $\mu\text{T}$ ) in order to observe the immediate effects on the central nervous system. It aims to establish the scientific basis for setting exposure limits. RTE and other electricity sector players like HydroQuébec, National Grid and the Electric Power Research Institute (EPRI) have been supporting this program for more than 10 years. The best known and best documented effects are magnetophosphenes, i.e. flashes of light that are perceived during high exposures to EMFs. The study is also looking into more subtle effects such as postural stability, reflex movements, cognitive reasoning, and memory.

RTE is providing technical input to two external epidemiological studies: **GEOCAP** and **CohoRTE**. **GEOCAP** (geolocation of paediatric cancers) is a case-control study being led by INSERM (National Institute of Health and Medical Research). It is analysing the residential environment of children with leukaemia and comparing it with that of a control population of children. This is a multifactorial study, since high-voltage lines and ELF-EMFs are just two factors among many others.

**CohoRTE** is an epidemiological cohort study of a group of retired RTE workers who were exposed to EMFs in their various jobs: maintenance of installations, and live-line working in particular. The health of this population will be monitored over time, and compared to that of the wider population. With the participation of RTE's occupational health team, this study is co-led by epidemiologists from EDF's Department of Medical Studies (EDF-SEM) and the consultants CEMKA-EVAL. A first publication was issued in 2020 but, as the cohort was only recently recruited, there are still few medical events to report.

## WHAT DOES THE LAW SAY?

Regulations in the Technical Decree of 2001 set exposure limits for the general public (100  $\mu\text{T}$  and 5000 V/m).

In 2011, a decree established Technical Inspections of Installations and Inspection and Monitoring Plans for EMFs. The application orders reiterated 100  $\mu\text{T}$  and 5000 V/m as limit values not to be exceeded in areas accessible to third parties.

The ministerial order of 15 April 2013, referred to as "Batho", is based on the precautionary principle. It recommends restricting the construction of buildings that will be used by risk-sensitive members of the public (hospitals, nurseries and schools) in the vicinity of power lines that exceed a so-called "precautionary threshold" of 1  $\mu\text{T}$ . This ministerial order, though non-binding, is a major challenge for RTE. In fact, taken word for word, it does not apply to RTE's installations but rather to construction projects nearby. Nevertheless, there is a general tendency to widen its scope. This order therefore strongly burdens network development projects in urban areas.

In addition, this ministerial order is sometimes factored into local urban planning, so that what was initially only a non-binding recommendation is occasionally transposed into a strict prohibition.

## Internalising the precautionary principle

The challenges of “EMFs and health” include numerous significant issues, notably in relation to communication and image. Conversely, the health risks are uncertain but limited and, in any event, the health impacts are minor as regards public health. The health implications are therefore small.

From a legal point of view, case-law regarding human health works out in favour of RTE. In 2 decisions<sup>5</sup>, the Conseil d’État ruled in particular that the information supplied, the risk assessment, and the measures adopted by RTE to manage the risks, had been sufficient and balanced. The legal issues have therefore been addressed, though vigilance is still called for, as case-law may evolve.

In terms of communication and image, it has to be conceded that the absence of evidence of a health impact on the one hand, and compliance

with regulations on the other, are not enough to reassure the public. This contradiction strains RTE’s relations with those living near its installations. This is a key internal priority for RTE: convince that the company position is ethical, and bring peace of mind to those who daily deal with this matter, such as the advisors and managers responsible for relations with third parties. RTE aims at achieving this priority by applying the precautionary principle, in order to be able to show that the company is acting for the best, under the framework of its public utility mission, and based on current knowledge.

This process requires continuous risk assessment (through scientific monitoring actions), transparent and reliable information and, finally, risk reduction by means of responsible power network management and development.

### A LOOK AT OUR EUROPEAN NEIGHBOURS:

The limit value of 100  $\mu\text{T}$  is the reference value across the European Union, though some countries (Austria, Finland, Germany) have adopted the new 200  $\mu\text{T}$  limit put forward by the International Commission on Non-Ionising Radiation Protection (ICNIRP). Many countries, including France, have implemented non-binding recommendations, in line with the precautionary principle. Italy and the Netherlands are the only countries to have set low regulatory limits (3 and 0.4  $\mu\text{T}$  respectively), which apply only to new installations.



#### Further reading

- **Clef des champs (A key to electromagnetic fields)** (RTE information website): <https://www.clefdeschamps.info/>
- **Comprendre les champs électromagnétiques d’extrêmement basse fréquence (Understanding extremely low frequency electromagnetic fields) (MOOC)**: <https://mooc.cem-50hz.info/>
- **Effets sanitaires liés à l’exposition aux champs électromagnétiques basse fréquence (The health effects associated with exposure to low-frequency electromagnetic fields)**, giving the views of ANSES (French Agency for Food, Environmental and Occupational Health and Safety), 2019
- **Champs électriques et magnétiques engendrés par les réseaux de transport. Description des phénomènes. Guide pratique de calcul (Electric and magnetic fields generated by transmission systems. Description of the phenomena. Practical calculation guide)**, CIGRÉ brochures - WG 36.01, Technical Brochure 021 (1980)
- **Responsible management of electric and magnetic fields (EMFs)**, CIGRÉ brochure - WG C3-19, Technical Brochure 806 (2020)

5. Rulings on the conformity of the Déclarations d’Utilité Publique (Declarations of Public Interest) for the projects in Cotentin-Maine and Avelin-Gavrelle.



# WEATHER, CLIMATE AND ENERGY, BETTER FORECASTING FOR BETTER FORWARD PLANNING

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**Laurent DUBUS** |

Distinguished Expert,  
Weather and Climate

At RTE, knowledge of weather and climate is becoming increasingly important for real-time management of the electricity system, for prospective studies related to the energy transition, and for studies of the network's resilience to climate change. The growing share of intermittent renewable energies (wind power, solar power) in the generation mix, a key component of this energy transition, will greatly increase the electricity sector's dependency on climate conditions. Efficient integration of intermittent renewable energy in electricity systems will also be dependent on improvements in modelling and forecasting it.

**Meteorology and climate science: two different timescales for two complementary fields of knowledge. The timescales for weather range from nowcasting to 10- to 15-day ahead. Climate refers to longer term weather patterns, and itself encompasses other aspects depending on whether the focus is the past, forecasts over a few months, or possible future scenarios.**

Weather and climate relate to natural processes, and their description draws primarily on the laws of physics. A set of equations (fluid mechanics, conservation of mass, heat) that are highly complex, very non-linear, and impossible to solve with any degree of accuracy except in simplified cases, an option that is very useful for explaining some key phenomena. But digital modelling is required if we are to solve these equations for the purposes of forecasting.

The basic principle of numerical weather and climate models is the representation of the atmosphere as grid-cells within which equations are solved using numerical methods, the result being a uniform value for every parameter inside each cell. The cells jointly form the grid of the model. The smaller the cells, the more accurate the model. The larger the grid size, the more the result is “smoothed out” over both space and time.

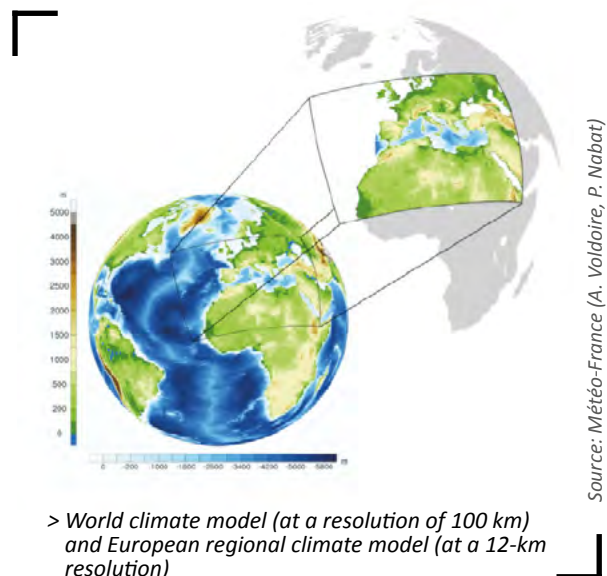
It makes obvious sense that small grid cells (high resolution) allow for better representation of physical phenomena, whereas large grid cells (low resolution) will only give a satisfactory representation of the larger-scale phenomena. For example, the **AROME** model used by Météo-France, which now operates with a resolution of 1.3 km, accurately predicts some very localised phenomena such as Cévenol episodes (heavy rainfall and flash floods in the Cévennes area of France), which a 20 km resolution cannot.

### A global or regional model

Another important factor is the model’s coverage: a global model covers the whole Earth, while a regional model covers a limited area of the globe (see illustration). At Météo-France, the **AROME** model is thus a regional model covering France and surrounding areas, and **ARPEGE** is the global model.

As the equations describing changes in the atmosphere are very non-linear, they can produce very different outcomes for very similar initial conditions (a phenomenon known as the butterfly effect). A forecast can therefore deviate significantly from the

actual situation after several days. This problem is mitigated by using ensemble forecasting techniques, which involve performing multiple simulations (generally between 20 and 50) using similar initial conditions. This ensemble of simulations delivers estimates of the probabilities of one condition or another. This probabilistic information is more difficult to conceptualise and use but is more robust and more reliable.



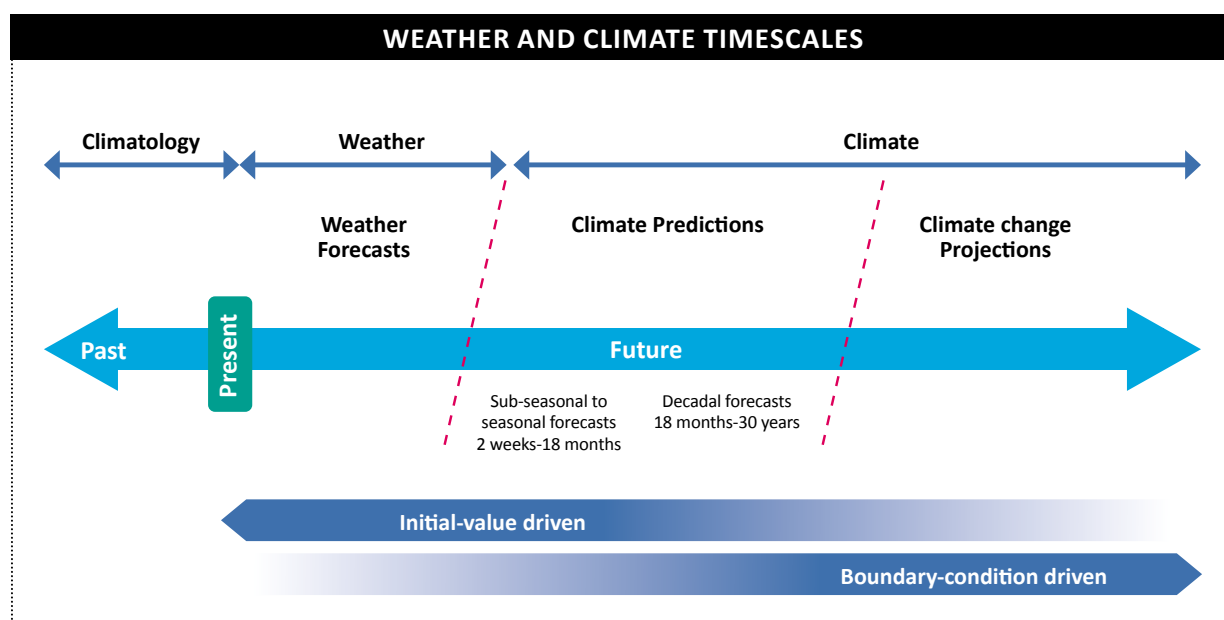
### The long term and climate

Different timescales yield different aspects of climate information. “Climatology” is a statistical description of the averages of different variables, over long periods of time that factor in year-to-year variability. The WMO (World Meteorological Organisation) has set a 30-year period of reference as a definition of climatology. “Climate forecasts” are designed to provide monthly, seasonal and ten-year forecasts, in which observation-based model initialisation is important. Finally, “climate projections” aim at providing potential future scenarios taking into account both natural external factors (solar activity, volcanism, etc.) and anthropogenic ones (greenhouse gases, aerosols, etc.), and examining several emissions scenarios for the latter.

Knowledge of the initial conditions is critical for short-term forecasts, but no longer critical for modelling time periods of more than a few days. For such timescales, it is important to take account of boundary conditions associated with interactions between the atmosphere and the other components of the weather system (oceans, glaciers, biosphere), which evolve more slowly but are nonetheless significant in the physics of the overall system. In practice, the models are gradually made more complex depending on the target time horizon. Coupled ocean-atmosphere models are used for sub-seasonal and seasonal forecasts (from two

weeks to a few months). For longer lead times, the models generally incorporate more factors: vegetation models, sea ice models, atmospheric chemistry models, etc. The key feature of these models is their inclusion of IPCC greenhouse gas emission scenarios.

As the models become more complex, they lose resolution. Today's climate forecast models typically have resolutions of the order of 20 to 50 km (sub-seasonal predictions), 80 to 150 km (seasonal predictions) and 50 to 200 km for climate projections.



## Expertise supporting the energy sector

The energy sector is a major user of weather-climate information and has been for decades. The information is mainly used for the short term to predict electricity consumption and, in particular, renewable energy production.

In the electricity sector, the use of weather forecasts for power consumption prediction is one of the oldest uses of weather forecasting, particularly in France where the development of electric heating in the 1970s and 1980s made consumption highly temperature sensitive.

Since the 1990s, and even more so since the 2000s, the significant growth in renewable energies - first wind power and then solar power - paved the way for new applications for predicting power generation from these highly intermittent sources. Many companies are now able to provide “energy” prediction products (electricity and gas usage, wind and solar power generation, market prices) using often very similar methodological approaches.

Recent advances in modelling have primarily been the result of a creative interaction between enhanced data availability and understanding of data (consumption data, production data), the implementation of additional prediction methods, drawing on several weather models, and the use of real-time consumption and production data to rectify the prediction models.

### Sub-seasonal and seasonal timescales, and long-term projections

The issue of climate change and the need to assess its impacts has led to the development of new applications. At present in the energy sector, sub-seasonal and seasonal timescales are addressed from a climate perspective: sets of observations from the past, or simulations of the past, are taken as likely future prospects. This approach therefore considers that past conditions are representative of what is going to happen in the near future (from a few months to a few years ahead).

That is a sensible approach for a stationary climate. But it is no longer robust in the context of climate change. Sub-seasonal and seasonal forecasting has changed significantly in the last 20 years, and several recent projects are beginning to produce concrete applications. For example, monthly forecasts to 45 days are now being trialled by RTE, particularly for the power system seasonal outlooks. The reference data is modified according to predictions updated weekly, to ensure that simulations take into consideration the best available forecasts in real time.

For long-range studies, the most common approach in the energy sector is to use past data, as with seasonal forecasting. Apart from academic researchers, few stakeholders in the sector have up to now used climate projections. For its part, RTE is ahead of the game and is using - including in its study **Futurs Énergétiques 2050** (Energy Pathways to 2050) - so-called “constant climate” scenarios developed by Météo-France. These scenarios provide 200 simulated years that are representative of the

climate in the 2000s, on the one hand, and in the 2050s, on the other hand, based on 2 greenhouse gas scenarios put forward by the IPCC. RTE’s R&D is now looking at the possibility of turning to more comprehensive projection ensembles that consider several climate models, as well as the dynamics of change throughout the 21<sup>st</sup> century.

## RTE’S PARTNERS

- **Météo-France** is RTE’s longstanding partner for weather and climate. It is a first-class provider of meteorological services in France and abroad, with a central role in RTE’s weather and climate activities.
- **The Institut Pierre Simon Laplace** in France is another international leader in climate modelling and, for some years now, in climate services. A joint effort is underway to explore new avenues for incorporating climate change into RTE’s studies, making the best possible use in particular of the latest climate projections available since the publication of the IPCC’s 6<sup>th</sup> Report.
- RTE is also working closely with the **École des Mines de Paris** (engineering school) on climate and energy issues, among other things. A Chair in “Data science applied to solar energy for the energy transition” has just been created with the school’s OIE Laboratory (Observation, Impact, Energy).
- At international level, the **World Energy & Meteorology Council** (WEMC) has become a major player in climate services for the energy sector. It is a non-profit organisation. The purpose of the WEMC is to bring together experts from the energy industry and the weather-climate community, to work together and share knowledge and experience in support of a transition to sustainable, resilient, and efficient energy systems. RTE has been a corporate member since 2020.

## ○ RTE: monitoring and forward planning with increasingly effective tools

The European Green Deal sets ambitious targets for reducing greenhouse gases emissions, and renewable energies are one of the pathways to these targets. The next few decades will see very significant development in renewable energies. The growing share of these energies will substantially increase the electricity sector's dependency on climatic conditions, owing to the considerable variability of renewables, which will impact the supply-demand balance (SDB).

The challenges of SDB are essentially twofold: the short term and the long term. In the coming years, the penetration of variable renewable energies will be greatly facilitated by improved forecasting of electricity output (better real-time estimation of production, refinement of short-timescale prediction). New approaches will also be required as far as possible to predict net consumption (consumption minus renewable energy production and self-consumption).

For the long term, it is going to be necessary to study the future operation of the electricity system using several parameters. These will include: a high penetration of renewable energies (local and national

generation, the need to reinforce interconnections, the need for flexibility with dispatchable energy sources and with demand), a change in energy usage profiles (roll-out of heat pumps, electric vehicles), and different temperature sensitivity (fewer cold spells in winter, more heatwaves in summer). Other factors to consider are: probably worsening operating conditions for thermal generation (loss of yield for nuclear power plants owing to higher temperatures, increased frequency and duration of their unavailabilities due to low flow rates and/or high water temperatures), and a possible reduction in hydropower generation (more intense/frequent heatwaves and droughts).

Aside from SDB issues, the power network itself is subject to climate hazards, and in the coming decades will face conditions that had not necessarily been anticipated in its initial design. The risks to the existing network must therefore be assessed in light of future climate conditions, both extreme (infrastructure resilience to climate stresses) and "average", as regards for example a decrease in possible power flows in the transmission lines in higher average temperature conditions.

### THE RESILIENCE PROJECT

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RTE has invested in installations that are in some cases designed to last several decades. It is therefore vital to identify potential vulnerabilities in the existing infrastructure, power line and cable connections, and substations, particularly in relation to temperatures and flooding. RTE must also look into the alignment of its technical requirements with the future climate, and amend them if needed, in order to design infrastructure that is climate-change resilient.

RTE therefore decided to launch the **Resilience** project, which aims to bring out these vulnerabilities based on climate projections for 2050 that draw on several IPCC scenarios. Regarding the heatwave hazard, calculation methods have been developed for overhead lines, underground lines, and power transformers. The objective is to extend these calculations to the whole infrastructure, and to compare results based on the three climate scenarios used by RTE.

As for the flooding hazard, in 2021 RTE entered a partnership with the Caisse Centrale de Réassurance (state-owned reinsurer). On behalf of RTE, it will model the water levels reached in substations and near pylons close to riverbeds to define different frequencies of occurrence. The modelled events will include river overflow, river overflow runoff, and coastal flooding.



### Regional and local studies

The future power network also needs to be designed by factoring in, at the design stage, the climate conditions under which new equipment and infrastructure will have to operate in up to the end of the century. Once again, this entails estimating all the climate conditions in which the network will have to be able to function, from normal to extreme conditions.

In addition, although climate change requirements have thus far been primarily addressed at a national level, regional or even local solutions are becoming increasingly important. One example is the challenge of downscaling climate scenarios for local network development studies.

Lastly, societal changes will have an impact on the distribution of power supply at a local level. These changes include movements of populations: “migrations” from the South to the North of the country to escape high temperatures (seasonal or permanent migration), and possible relocation of economic activity shifting the distribution and weighting of energy consumption zones. There may also be larger-scale impacts from the reshoring to France of activities currently carried out abroad, as part of a national commitment to industrial redevelopment.

### More and more climate services

The challenges are thus wide-ranging, and the underlying issues complex. The plan is not for RTE and its R&D department to manage everything in-house, but rather to find the right degree of interface with the “outside” world, whether academic, institutional, or private.

The need for climate services to offer information on long-term issues was formalised at international level during the Madrid Conference organised by the WMO in 2007. Since then, climate services have evolved considerably, both worldwide with the Global Framework for Climate Services, and at regional and national levels. The European **Copernicus** programme monitoring the Earth (see box), backed by multiple research projects, has now become a world reference.

Alongside the development of climate services, other key advances have changed the paradigm of meteorological and climate modelling. The main advancement has undoubtedly been the massive

development and practical applications of augmented intelligence. The use of augmented intelligence is widespread, from short-term forecasting of renewable energy generation to automated processing of large volumes of data for climate projections.

Weather forecasts and climate simulations will continue to advance at a sustained rapid pace. Given the growing challenges facing the electricity system, RTE must maintain its resolute stance on the subject in order to take advantage of the best information and models available worldwide.

## **COPERNICUS THE EARTH AS SEEN BY EUROPE**

Europe today is the most advanced continent in terms of the development of climate services. This development has been driven by a multitude of research projects and programmes such as **Horizon2020** and **Copernicus**.

**Copernicus** is Europe’s programme for monitoring and forecasting the Earth’s environment. It is coordinated and led by the European Commission, and is made up of 6 areas of focus, which include the Copernicus Climate Change Service (C3S) dealing specifically with climate services.

Set up by the European Centre for Medium-Term Weather Forecasts, C3S has several components. The two main constituents are the Climate Data Store, a large supermarket of past, present and future climate data, and the Sectoral Information System, which develops tailored applications for specific issues, currently covering a dozen sectors including water and energy, and due to expand further.

Access to **Copernicus** data (and thus to C3S) and the use of this data is completely open and free. The programme is underpinned by agreements with universities, public bodies including meteorological centres like Météo-France, and private companies.



## Further reading

- **Météo et énergie : la collaboration au service de la transition énergétique (Weather and energy: cooperation for the energy transition)**, L. Dubus - Revue des Mines, N° 495 (Janvier 2018).
- **Weather Matters for Energy**, A. Troccoli, L. Dubus et S-E. Haupt - Springer (2014).
- **Weather and Climate Services for the Energy Industry**, A. Troccoli - Palgrave Macmillan (2018).
- **A Comprehensive Wind Power Forecasting System Integrating Artificial Intelligence and Numerical Weather Prediction**, Ouvrage collectif - Energies (2020).

# A POWER NETWORK IN CONSTANT INTERACTION WITH BIODIVERSITY

© Lisa Garnier



**Lisa GARNIER** | Distinguished Expert, Biodiversity

As an electricity transmission system, RTE's infrastructures form an integral part of the environment. This environment encompasses climatic, physical and biological components, from water, wind and hail to living organisms. In a very real way, RTE interacts daily, to a greater or lesser extent, with biodiversity.

But we cannot ignore the context of the mass extinction of species that is currently underway: a growing number of studies are confirming that the current rates of extinction are a hundred times higher than those seen throughout the planet's geological history. RTE is thus operating in a world that has entered a 6<sup>th</sup> mass species extinction.

The very familiar word ‘biodiversity’ embraces a multitude of theories derived from different fields of study. This is because, while the living world comprises a variety of organisms, they vary above all in terms of the diversity of their interactions and evolution over time. Thus, biodiversity is defined as the totality of relationships established among living organisms, and between them and their environment, across different spatial scales (from genes to landscapes) and timescales (geological time up to the present).

RTE’s infrastructure<sup>1</sup> interacts with its environment both directly and indirectly. This must be factored into its entire lifecycle.

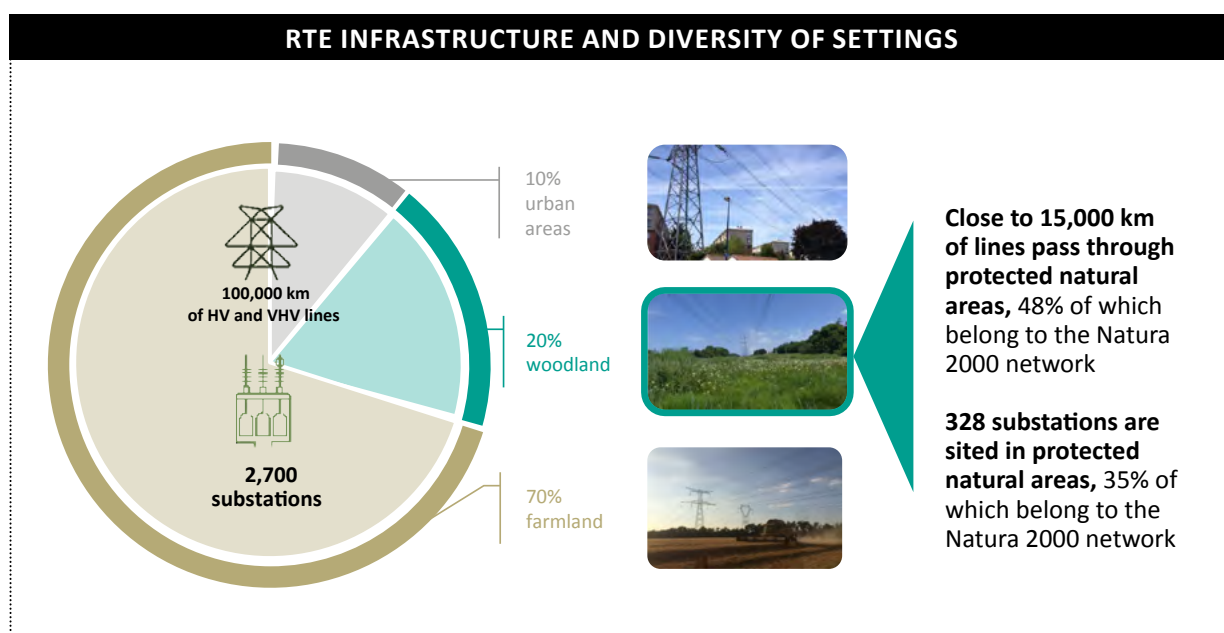
Since infrastructure consists essentially of technical objects, indirect interactions take place from the moment a piece of infrastructure is envisioned and the raw materials have to be ordered from suppliers. These interactions must therefore be taken into account from upstream of the first construction sites, in the course of power network studies, of engineering studies, and at the stage when the suppliers manufacture the equipment.

The direct interactions appear more straightforward. But the impacts of infrastructure are wide-ranging, can accumulate, and can be positive, negative, or neutral (see box).

On land, power lines run through the air at different

heights. And living organisms that fly (mammals, insects and birds) may come into contact with these electric lines. At ground level, the power lines mark out a ground footprint in which a minimum safety distance is required between the installation and vegetation (technical decree of 17 May 2001). Depending on the height of the power lines, changes to the natural environment of each footprint, which must be managed differently, have an impact on biodiversity.

In addition, pylons are structures that establish a connection between ground and air. Species living on the ground may find them useful (as resting places, feeding stations, breeding grounds) if they are able to climb the structures. Similarly, species that fly may also find a use for pylons. Substations also offer a footprint and structures on which flora and fauna can settle, move around, land and even reproduce.



<sup>1</sup>. Infrastructure refers here to all the constituents of RTE’s assets and activities (buildings, electrical equipment, dispatch centre, substations, pylons, vehicles, digital infrastructure, etc.).



Finally, underground or submarine cable connections impinge on the ground or seabed at the expense of the organisms there (mammals, micro-organisms, insects, crustaceans, molluscs, annelids). Like overhead power lines, they may have an impact on these species.

Since the 2000s, there have been a growing number of scientific studies examining the impacts (positive or negative) of high-voltage power lines on biodiversity. Among vertebrates, birds are the main focus of studies. But research is also taking place on plants and invertebrates, and insects in particular.

## OVERVIEW OF THE DIFFERENT EFFECTS OF INFRASTRUCTURES

The most common impacts of land-based power lines are barrier effects (impediment to movement) and resource effects (attraction) created by changing the habitat. Despite the predominance of negative impacts for each of these effects, a modified habitat, along with edge effects and corridor effects, brings to light some positive impacts.

- **Barrier effects**

The appearance of a new structure in a landscape can form a physical barrier (an overhead power line, for example) and create a risk of collisions. To date, barrier effects have mostly been studied for birds, which can be forced to adjust their flight paths. But power lines can also impede the movement of small mammals, indicating reduced forest connectivity.

- **Power lines as resources**

Electricity cables and pylons can serve as perches, resting places, and breeding grounds, thereby extending the distribution of some bird species. Studies have shown that electricity infrastructures could offer refuge in habitats with little variety, and that vegetation underneath pylons could benefit birds, insects, and small mammals.

On the other hand, these same structures cause the most accidents, the electrocution of birds of prey in particular. For RTE, avian collisions are the most common type of accident.

- **Habitat change**

Depending on the initial type of environment, the cutback of vegetation underneath power lines is destructive, but is also beneficial for some plant and animal species by opening up the area and changing the ecosystem. For example, the formation of “young” habitats created by regular cutback

allows groups of species that are dependent on open spaces (grasses, insects) to multiply, and enhances landscape heterogeneity between each cutback.

- **Habitat fragmentation**

The fragmentation of habitats refers to human activity “nibbling away” at the initial habitat, which is reshaped into multiple smaller habitat fragments. Current research on terrestrial environments has not identified major negative impacts from electricity transmission networks.

- **Edge effects**

Edge effects stem from an increased boundary area between two ecosystems, giving rise to changes in groups of species and in environmental factors (sunlight, for example). These edge effects appear in particular when the vegetation inside a footprint area is cut back.

- **Corridor effects**

Corridor effects refer to easier movement of species between two habitats that had been fragmented. Such effects have not been recorded for power lines.

- **Electromagnetic fields**

There has been little research into the effects of electromagnetic fields on wild species. Some work has been carried out on certain bird species, and on the biochemical mechanisms of plants. As for the marine environment, there are a growing number of research projects on different species.



### From regulation to partnership

Generally speaking, because the nature of the interactions with biodiversity was never understood other than in terms of predation - which is one of the reasons why biodiversity is threatened with extinction - the responsible authorities such as governments, intergovernmental services and the European Union developed regulatory instruments to ensure the protection of biodiversity. In France, a distinction is therefore made between regulations governing protected species and regulations governing protected areas. These regulatory protection measures are factored into impact studies prior to the construction of a new installation. Many regulations are also in place to protect biodiversity in the course of maintenance operations (painting of pylons, cutback of vegetation in forest corridors).

This profusion of regulations and associated structures commit RTE to interacting with multiple bodies responsible for managing natural areas: biodiversity has become a motivating force for human interaction. Its preservation is a driver of collaboration and an urgent call to dialogue. The relationships between different stakeholders (residents, subcontractors, local government) can therefore become a win-win partnership or, failing that, an objective to aim for so as to avoid wasting effort and resources on disagreements. The notion of ecosystem services provided by biodiversity - defined as the benefits that humans draw from ecosystems - offers RTE

the opportunity to put forward land management proposals that support biodiversity, while fostering positive regional dialogue that builds consensus.

### THE CILB: A PROACTIVE COMMITMENT

RTE's current partnerships have been built over time through local projects (the first planned management by hunters of areas at the base of pylons, in 2004) and commitments made in response to the Grenelle Environment Forum in 2007. The Linear Infrastructure and Biodiversity Club (CILB), of which RTE is a founder member, seeks for example to achieve shared biodiversity preservation and regional development objectives. It is actively involved in the Land Transport Infrastructure, Ecosystems and Landscapes (ITTECOP) research programme with the Ministry for Ecological Transition and the Foundation for Biodiversity Research.

CILB has 10 members, including EDF, Enedis, GRT Gaz, SNCF Réseau (national rail network), Eiffage, and les Voies Navigables de France (waterways authority).

## ○ R&D for better integrated and more resilient infrastructure

With the collapse of biodiversity compounded by global warming, the management of flora and fauna is expected to be taken into ever greater consideration at a regional level in infrastructure development projects, particularly with species reintroduction programmes. Much research is still needed and RTE is committed to focusing its research on avifauna and on ground-level, below-ground and marine environments.

Research into aerial species phenomena primarily covers birds but can also include other flying animals such as bats. RTE's pylons are used by many bird species as perches, resting and nesting places. For several years now, the numbers of white storks

nesting on pylons have been increasing.

As an example, in the Loire-Atlantique region, 25% of stork nests are now being built on RTE pylons due to loss of trees. The presence of these nests imposes constraints (laws governing protected species) and additional maintenance measures associated with installing equipment (safe relocation of nests, installation of perch-deterrents) and the regular monitoring of installed equipment (cutback of branches). This also has an impact on the quality of the electricity and therefore on relationships with customers. From 2009 to 2018, the compensation costs of poor service quality attributable to storks amounted to 8 million euros in the Western part

of the country. This is a low estimate as it does not take account of the financial impact (equipment, manpower, installation reinforcement studies).

### **Making power lines safe by 2050**

The solutions to enable safe interactions between infrastructures and birds have several aspects. It is important to understand the behaviour of birds near the lines, and to study the effectiveness of line hazard markers. It is also essential to assess objectively the constraints and benefits of allowing some bird species to nest on pylons underneath the conductor cables, particularly in agricultural settings, or above conductor cables, depending on the level of regulatory protection that applies to the birds. Lastly, it is important to develop new line hazard markers (drawing on knowledge of bird vision, behaviours, and migration routes). The objective is to enhance the methods used (impact studies, monitoring, compensation habitat) to make optimal use of available resources so as to provide safer power lines by 2050 for the species most at risk.

In addition to the studies of direct interactions (e.g., the effectiveness of anti-collision procedures), research can also focus on win-win interactions. This involves in particular increased biodiversity resilience, better acceptance of installations, and therefore greater optimisation of electricity network developments.

### **Research on land related issues**

According to the IPCC scenarios, climate change will have consequences for fire hazards, primarily due to increased periods of drought. There will also be an impact on soil quality (moisture levels and soil structure). Although alternative management of vegetation is one approach under development, RTE will also have to seek other innovative solutions, in response particularly to the current decline in farmed land, which is reducing the number of potential partners.

These solutions must simultaneously integrate RTE's footprints and substations in their surroundings, meet the challenges of biodiversity conservation, ensure resilience to future fires, and fight against climate change through carbon storage.

In order to go beyond mere regulatory preservation of biodiversity, RTE could act as a supportive "link" between all the stakeholders of the power line

corridors: customers, farmers and foresters, etc., thereby making the company a major player in the regions. More research is needed in these areas of focus so as to examine solutions and technical feasibility.

Furthermore, studies and projects are already in progress. Since 2018, RTE has ramped up its commitment to a voluntary strategy of gradually removing plant protection products from the management of its industrial sites. For substations, land management work was initiated in 2011, in keeping with the commitments of the EcoPhyto plans and water regulations, to proactively trial different solutions for zero use of plant protection products (suitable vegetation, ground cover, mineral mulch). Different trials have been carried out for land maintenance, including environmentally friendly animal grazing, and the use of robots. Biodiversity is monitored as part of a protocol developed with the Muséum National d'Histoire Naturelle (Natural History Museum).

### **Research linked to underground or submarine power cables**

Globally, although approximately 25% of the world's recorded biodiversity lives underground, very few studies have focused on this environment in terms of its interactions with underground cable systems. Further research is needed to understand the effects of underground cabling on biodiversity below ground, prior to any potential regulation on the matter.

In a marine environment where interconnections and power cables are being developed for offshore wind farms, the potential temporary impacts include the noise generated during installation work, changes to the substrate (seabed), and turbidity. The potential permanent impacts are associated with electric and magnetic fields, and reef effects. There are uncertainties in these areas despite advances in scientific knowledge. The level of disruption is dependent on where the power cables are sited: in the water column (dynamic cables to connect floating wind farms), on the seabed (laid and protected cables) or in the sediment (embedded cables).

As early as 2011, RTE has agreed with IFREMER (National Institute for Ocean Science) to gather information on the impacts of submarine power cables during installation and operation. A summary of the findings was published by IFREMER in 2019. It indicated that the ecological impacts of submarine power cables are comparable to the standard

environmental issues inherent in any artificial structure installed on the seabed, and for which there is generally extensive scientific knowledge. The summary report also raised less studied questions on voltage flows in cables (electromagnetic fields, overheating). The summary report did not flag up any impacts that were deemed to be of major importance.

**The marine ecosystem: 17 projects, including a Chair in Marine Studies and two literature reviews**

RTE and its partners are carrying out several types of studies to meet the challenges of offshore project development. Nine research projects on marine biodiversity and marine ecosystems are ongoing (the remainder having been completed).

Some projects (see illustration) are looking at the potential effects of the installation and operation of submarine cables. Thus, the **OASICE**, study, launched in 2017, is focusing on the effects of turbidity, acoustics, and electromagnetic fields. **OASICE** is seeking to validate the use of scallops as bio-indicators.

## **A WEALTH OF PARTNERS**

RTE is establishing numerous non-profit, academic and institutional partnerships to carry out its research. Thus, the company is working with partners such as the Ligue de Protection des Oiseaux (Society for the Protection of Birds), bodies in charge of managing natural areas (the Federation of Regional National Parks, for example), the Muséum National d'Histoire Naturelle (Natural History Museum), IFREMER, and the Office National des Forêts (National Forestry Board). Other key partners for RTE include CNRS (National Centre for Scientific Research), the University of Western Brittany, France Énergie Marine, The University of Caen, and specialist consulting firms Ecocéan, TBM Environnement and Créocéan.

Other studies are defining the dynamics of the environments in which future fixed or floating offshore wind farms will be sited, along with their cable links. This is the case of the **DUNES** project (Dunkirk) and **APPEAL** project (a floating wind farm pilot project, Groix and Belle-Ile). These local studies provide an understanding of the initial environment as well as the dynamics of species, prior to an infrastructure installation at sea, so as to model future changes in the light of environmental variations: climate change, shifts in usage, introduction of an infrastructure.

Finally, committees of experts such as **GIS ÉCUME**<sup>2</sup> or **COME3T**<sup>3</sup> perform more cross-cutting studies.

If the aim of all this research is to minimise impact and regenerate biodiversity, more effort is needed to understand the ecological mechanisms linked to the presence of submarine power cables and offshore substations, particularly where there is a high or medium degree of uncertainty. Reducing these uncertainties will tend to produce a lower risk perception.

Since this is a relatively new topic, most areas in it need investigation. At the installation stage, knowledge of the impacts of the works over time and space will help improve and develop avoidance actions. During operation and maintenance, research will be able to show the potential impact of electromagnetic fields on vulnerable migratory species. Studies will shed light on the role of reef effects and on their ability to regenerate marine ecosystems. And for both terrestrial and aerial species, better knowledge paves the way for enhanced nature-based solutions and for constructive dialogue with stakeholders in the context of the energy transition.

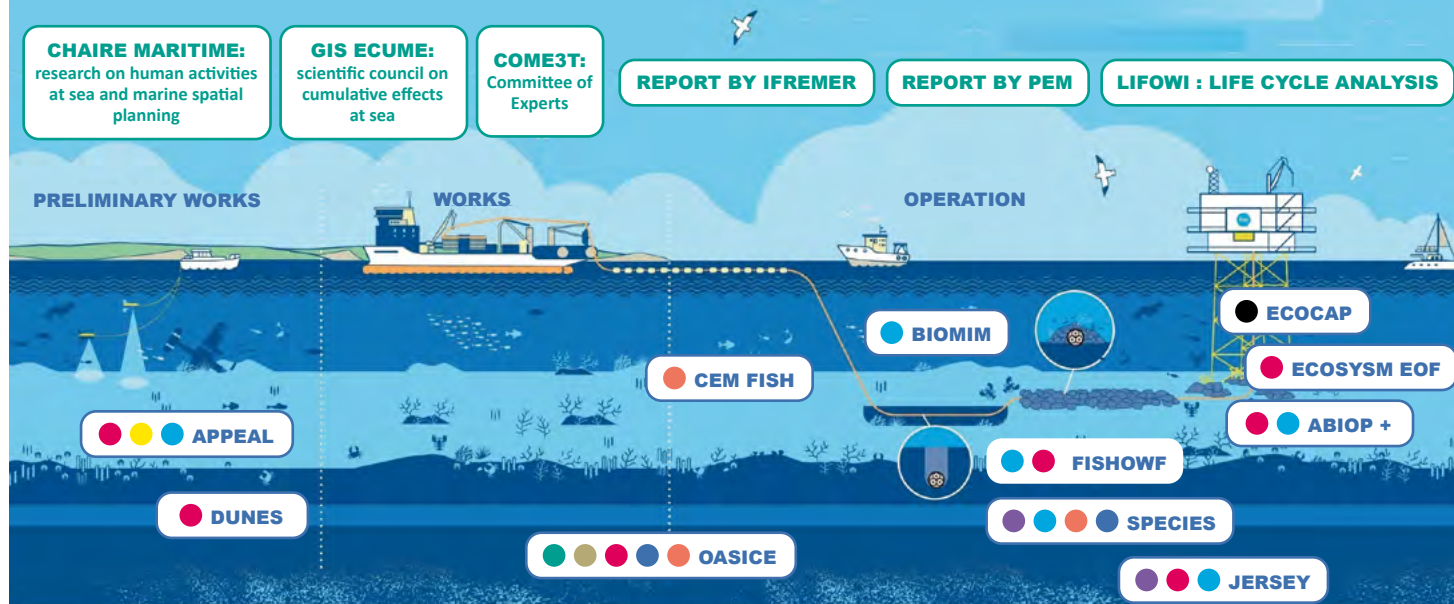
The objective of this research, clearly, is to create a safe alliance with biodiversity in three key areas: aerial, terrestrial and marine species. Building up the decisive knowledge is the key to innovation, adaptation, forward planning, and regeneration. Innovation will make it possible to delve more deeply into new topics. Adaptation will provide resilience. Forward planning will maintain performance. And regeneration will ensure that we stand by and support all lifeforms.

In due course, greater experience will allow us to move forward with the implementation of solutions that integrate and value all lifeforms, and arrive at an ecological power network.

2. Scientific Interest Group - Cumulative Effects at Sea.

3. Committee of Experts for the Environmental Issues Related to Marine Renewable Energies.

# MARINE BIODIVERSITY RESEARCH AND DEVELOPMENT STUDIES



## CAPTION

- Socioeconomic impact
- Habitat disruption
- Noise emissions
- Reef effect
- Electromagnetic field emissions

- Turbidity
- Thermal effect
- Reserve effect
- Chemical pollution

GLOBAL STUDIES

TARGETED STUDIES



## Further reading

- **Comprendre la biodiversité (Understanding biodiversity)**, Alain Pavé - Éditions Le Seuil (2019)
- **Biodiversité : L'avenir du vivant (Biodiversity: The future of life)**, Patrick Blandin - Albin Michel (September 2020)
- **La biodiversité, de l'océan à la cité (Biodiversity, from oceans to cities)**, Gilles Bœuf - Fayard
- **Sauvons la biodiversité ! 10 actions pour réagir (Saving biodiversity: 10 actions in response)**, Hélène Soubelet and Jean-François Silvain - Rustica Éditions (April 2019)
- **MOOC: Biodiversité et changements globaux (Biodiversity and global change) UVED web portal**  
<https://www.uved.fr/mooc-biochang>





### **BOISSET Jean-Marie**

Deputy Department Manager, Head of Systems Section  
CNER, Local PACS Department

Jean-Marie is a graduate of the École Supérieure d'Électricité. He worked for over 30 years on the development of substation protection, automation and control systems, first at GEC ALSTHOM and then at ALSTOM and AREVA, in the roles of development engineer, technical manager, project lead, and R&D director.

He joined RTE in 2010 to head the development of protection, automation and control systems.



### **CHABIN Sophie**

Expert  
CNER - SERECT

After graduating in general engineering with a specialisation in electrical engineering, Sophie joined EDF in 1996, working at SERECT as project lead responsible for developing live working tools. She worked on various tools, and discovered the world of standardisation and international projects.

In 2001, Sophie joined CNER to work on operating policies, before taking charge of quality management at CNER. She then pursued her career in Lille, in the Network Maintenance Engineering Group, overseeing policies for overhead power lines, including mechanical reinforcement, rehabilitation, and paintwork.

In 2011, she returned to SERECT to head up the section tasked with development, testing, and technical support. Today, at SERECT headquarters, Sophie is the Rapporteur for the Live Working Committee, and Secretary of the IEC and CENELEC live working standardisation groups.



### **DESCHAMPS François**

Senior Project Manager  
Development & Engineering Division, Dialogue & Environment  
Department

François is a graduate of the École Nationale Supérieure d'Ingénieurs Électriciens de Grenoble (ENSIEG). Recruited by EDF R&D, he first worked on the measurement systems of high voltage electrical equipment testing laboratories, and then he specialized in electromagnetic fields. He joined RTE in 2000 as expert advisor on electromagnetic fields and their potential effects on living beings.

François is a member of several IEC and CENELEC standards committees, and has been a distinguished member of CIGRÉ since 2006.



### **DUBUS Laurent**

R&D Expert  
R&D Headquarters, Climate, Supply-Demand Balance and Long-Term  
Network Planning Section

Laurent is a researcher in the specialist field of weather and climate. His activities are focused on incorporating the best available weather and climate information into different electricity system control, management and planning processes, across all timescales. Having graduated in fluid mechanics, he is a general engineer specialising in the marine environment, and has a doctorate in physical oceanography. After working at EDF R&D, he joined RTE in 2019.

Laurent is co-founder and a non-executive director of the World Energy and Meteorology Council, an international non-profit organisation whose primary role is to foster cooperation between the weather-climate community and the energy sector.





### **GARNIER Lisa**

**R&D Lead for Networks and Marine & Terrestrial Biodiversity**  
**R&D Headquarters**

Lisa has a PhD in ecology and is a biodiversity specialist. She has worked for the Muséum National d'Histoire Naturelle in Paris. She was also scientific secretary to the Conseil Scientifique du Patrimoine Naturel et de la Biodiversité (CSPNB) (Scientific Council for Natural Heritage and Biodiversity), and senior adviser for biodiversity in the research department of the Ministry for Sustainable Development.

Since 2017, she has led RTE's marine and terrestrial biodiversity R&D projects.



### **HONDA Pierre**

**Expert, Underground and Submarine Cables**  
**CNER, Cables Department, Underground Cable Systems Division**

Pierre began his career at Bull before joining the Laboratoire de Génie Électrique (LGE) des Renardières at EDF R&D in 1993. There he carried out dielectric and power tests on a wide range of equipment, both low and high voltage, overhead and underground equipment. In 2000, he moved to the studies group, again at EDF R&D, to monitor the qualification of equipment up to 400 kV, and to conduct studies and expert appraisals following network failures, before joining RTE in 2008.

Pierre takes part in drafting the specifications for HVAC and HVDC underground and submarine cable systems.

He contributes to the working groups for cable systems in French and international standards development, AFNOR and IEC respectively.



### **LAJOIE-MAZENC Claire**

**Scientific Adviser**  
**European Industrial Affairs Project**

Claire began her career at EDF R&D in Clamart. She has been looking into energy storage for power networks for about 12 years, and set up a dedicated team at EDF R&D, and then a research programme. She first worked at RTE from 1998 to 2008, when she went back to EDF R&D, before re-joining RTE in 2016. Since then, she has helped build expertise on storage (supporting the launch of the Ringo and Osmose projects).

Claire set up and now chairs the Club Technique Stockage et Nouveaux Moyens de Production (New Generation and Storage Technical Team) for SEE (Association for Electricity, Electronics, and Information and Communication Technologies). She represents RTE at the European Association for Storage of Energy, and is a member of the ETIPs for Energy Transition and for Batteries. She has also been the president of the IEEE France Section since January 2020.



### **LE DU Marc**

**R&D Expert**  
**R&D Headquarters, Economics, Forecasts and Social Issues Section**

Marc holds a degree in engineering from the Université de Technologie de Compiègne, and a postgraduate degree in applied mathematics. Since 1992, he has led various research and development projects on the transmission and distribution systems, on the management of power generation, and on energy markets.

He joined RTE in 2016. Since then, analyses of the electricity system's transition to carbon neutrality have led him to work on the interactions between electricity and other energy carriers, carrier sector combinations, and the economics of energy systems.



### **LEFIEUX Vincent**

#### **Deputy Director for Statistics and Data Valorisation**

Vincent Lefieux has a PhD in statistics. He worked as a research engineer at EDF R&D before joining RTE R&D in 2003.

He has specialised in time series modelling (electricity consumption, renewable energy generation, etc.), and created and has led the Data Science and AI Section at RTE. Over the years, Vincent has also taught many courses in universities and engineering schools. He was associate professor at the Sorbonne University from 2010 to 2015.

Vincent is the chair of the board of directors of the Institut Henri Poincaré's endowment fund.



### **LEITLOFF Volker**

#### **Expert**

#### **CNER, Local Protection, Automation and Control Department, Service Levels and Performance Division**

A graduate in electrical engineering from the University of Stuttgart (Germany), Volker then wrote his doctoral thesis at the Laboratoire d'Électrotechnique de Grenoble (Grenoble Institute of Technology). He worked in EDF's Research and Studies Division from 1994 to 2002, focusing on electricity system protections and technologies. He joined RTE in 2003, in the specialist field of protection, automation and control systems.

Volker is president of the IEC's TC 38 and of CENELEC's TC 38 (instrument transformers) and coordinator for the IEC's TC 95 WG2 (protection functions with digital input/output).



### **PANCIATICI Patrick**

#### **Scientific Adviser**

#### **European Industrial Affairs Project**

Patrick is a graduate of the École Supérieure d'Électricité. He joined EDF R&D in 1985 and then RTE in 2003, contributing to the creation of an in-house R&D department at RTE. He has over 35 years of experience in the "system" aspects of large power systems. He currently energises and coordinates RTE's long-term research on these "system" aspects.

Patrick works closely with a large network of international experts, and is in regular contact with the world's leading teams on these topics. He is a CIGRÉ member, an IEEE fellow, and a distinguished member of SEE (Association for Electricity, Electronics, and Information and Communication Technologies).



### **PRIEUR Pascale**

#### **R&D Expert, Lead for the roadmap Modelling and Assessment for Behaviour Forecasting**

#### **R&D Headquarters**

Pascale joined EDF in 1990, at the Research and Studies Division (Chatou). She started out in the field of equipment monitoring and maintenance for the nuclear fleet. In 1997, she launched into the world of transmission systems, working as a product engineer for gas-insulated switchgear (GIS) equipment.

She joined RTE in 2001 and was in charge of the company's specifications for GIS equipment up to 2012. With the setting up of an Environmental Management System at RTE, in 2002, she became involved in the reduction of SF<sub>6</sub> emissions into the atmosphere.

Since 2014, at RTE's R&D, she has been the area lead for the Asset Management Programme. She continues her work on standardisation, notably in her role as president of CENELEC 17AC.



### **RIBOUD Jean-Christophe**

Senior Engineer

CNER, Substations Department, Transformers, Condensers and Components Division

Jean-Christophe is a graduate of the École Catholique des Arts et Métiers in Lyon, and of the Institut National Polytechnique de Grenoble / École Nationale Supérieure d'Ingénieurs Électriciens de Grenoble (ENSIEG).

Prior to joining RTE in 2007, he was technical director of the Alstom power transformer factory at St Ouen. He has devoted his career to power transformers and similar high-voltage equipment.

Jean-Christophe is currently chair of AFNOR committees UF 14 (transformers) and UF 36A (insulated bushings). At the IEC, he is leading the work of MT 60076-5 and of joint group TC 36A - TC 14 number 8. He is a senior member of the SEE (Association for Electricity, Electronics, and Information and Communication Technologies), and in 2015 he received the "Prix du Centenaire" (Centennial Award) of the Union Technique de l'Électricité (French electrical engineering standardisation body).



### **SERMANSON Vincent**

Senior Project Manager at SEDRE (Electricity System Development Studies Department)

Vincent joined EDF's R&D at Clamart in 1998, in the Electricity System Studies Department/ Electricity System Operation and Control, after completing a degree at the École Supérieure d'Électricité with a specialisation in electrical engineering, as well as a degree in management economics, and 16 months of non-military national service as a researcher at the Université of Liège (Belgium). In 2000, he was seconded to the Electric Power Research Institute (EPRI) in California for one year, to carry out a study on the reliability of the North American electricity network.

He joined RTE in 2003, in the Methods and Support Department in Versailles. In 2011, he joined SEDRE, which had been set up in Lille to carry out studies on the future of the 400kV and 225kV networks.

Vincent has been into many aspects of power system operation: from assistance with day-ahead operation to long-term development studies, from voltage collapse to inter-area oscillations, from the development of dispatcher training tools to the coordination of a European project, from the study of the 225kV/90kV network in Vendée to North American transmission systems, from IEEE conferences to ENTSO-E and CIGRÉ working groups.

# LIST OF ACRONYMS

<b>AC:</b> .....	Alternating Current
<b>AI:</b> .....	Artificial or augmented intelligence
<b>AST:</b> .....	Auxiliary service transformer
<b>ATEE:</b> .....	(Association Technique Énergie Environnement): Technical Association for Energy and the Environment
<b>CENELEC:</b> .....	(Comité Européen de Normalisation en Électronique et en Électrotechnique): European Committee for Electrotechnical standardisation
<b>CGCT:</b> .....	Combined Gas Cycle Turbine
<b>CIGRÉ:</b> .....	(Conseil International des Grands Réseaux Électriques): International Council on Large Electric Systems
<b>CNER:</b> .....	(Centre National d'Expertise Réseau): National Centre for Network Expertise
<b>CNES:</b> .....	(Centre National d'Exploitation du Système): National System Operation Centre
<b>CPSoS:</b> .....	Cyber-Physical System of Systems
<b>CRÉ:</b> .....	(Commission de Régulation de l'Énergie): Energy Regulatory Committee
<b>DC:</b> .....	Direct Current
<b>DSO:</b> .....	Distribution System Operator
<b>EASE:</b> .....	European Association for Storage of Energy
<b>EMFs:</b> .....	Electromagnetic Fields
<b>ENTSO-E:</b> .....	European Network of Transmission System Operators for Electricity
<b>ENTSO-G:</b> .....	European Network of Transmission System Operators for Gas
<b>EPRI:</b> .....	Electric Power Research Institute
<b>FAT:</b> .....	Factory Acceptance Test
<b>HV:</b> .....	High Voltage
<b>HVDC:</b> .....	High Voltage Direct Current
<b>IEC:</b> .....	International Electrotechnical Commission
<b>IED:</b> .....	Intelligent Electronic Device
<b>IEEE:</b> .....	Institute of Electrical and Electronics Engineers
<b>IPCC:</b> .....	Intergovernmental Panel on Climate Change
<b>LPIT:</b> .....	Low Power Instrument Transformer
<b>LPT:</b> .....	Large Power Transformer
<b>LV:</b> .....	Low Voltage
<b>LW:</b> .....	Live Working
<b>MPT:</b> .....	Medium Power Transformer
<b>PACS:</b> .....	Protection, Automation and Control Systems
<b>PHES:</b> .....	Pumped Hydro Energy Storage
<b>PPE:</b> .....	(Programmation Pluriannuelle de l'Énergie): Multiyear Energy Plan
<b>R#SPACE:</b> .....	RTE Smart Protection Automation and Control Ecosystem
<b>SAT:</b> .....	Site Acceptance Test
<b>SDDR:</b> .....	(Schéma Décennal de Développement du Réseau): TYNDP (Ten-Year Network Development Plan)
<b>SEDRE:</b> .....	(Service Études de Développement du Réseau Électrique): Power Network Development Studies Department
<b>SEE:</b> .....	(Société de l'Électricité, de l'Électronique et des Technologies de l'Information et de la Communication): Association for Electricity, Electronics, and Information and Communication Technologies
<b>SERECT:</b> .....	(Section d'Études, de Réalisation et d'Expérimentation pour le Comité Technique): Design, Execution and Testing Section of the Technical Committee
<b>SNBC:</b> .....	(Stratégie Nationale Bas Carbone): National Low Carbon Strategy
<b>TSO:</b> .....	Transmission System Operator
<b>TURPE:</b> .....	(Tarif d'utilisation des réseaux publics d'électricité): transmission network usage tariff

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