SYNTHESIS REPORT

Contribution to the national energy research strategy (SNRE)

How can we ensure power system flexibility?

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ASSOCIATION NATIONALE RECHERCHE TECHNOLOGIE

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THE POWER OF COLLECTIVE INTELLIGENCE

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EXECUTIVE SUMMARY

The growth of renewable energy (RE), in practice wind and solar power, has an impact on the characteristics and operation of the electricity grid. These sources are intermittent[1], and call on two sources of primary energy – wind and sun – which cannot be stored. This creates a much greater need for flexibility to tackle **differences between electricity supply and demand,** differences that are becoming larger and more frequent, sometimes requiring real-time responses from electricity system operators.

Making compromises with supply security is not an option in the energy transition, yet at times, simultaneously and over vast areas, RE produces insufficient electricity for several days, and the electric power system comes up against the **difficult problem of long-term storage.** It is also essential to maintain voltage stability and frequency, despite the absence of natural inertia in wind and solar power. Lastly, it is indispensable to **minimize the financial cost of the energy transition,** and flexibility needs to be employed to reduce overall investment, even though flexibility itself requires expenditure.

In addition, the production and transmission of electricity are increasingly decentralized following EU directives, the multiplication of RE producers (in particular solar), and the move towards self-consumption and more generally shorter production circuits. Advances in digital technologies open up the way to decentralize control and dispatch in the power system and to offer new services.

The need for flexibility is therefore part of a much wider shift, but it concentrates a great number of problems generated by the energy transition, and raises research challenges. For this reason, the ANRT working group chaired by Olivier Appert put the issue on its agenda for 2020, following two years of work firstly devoted to the balance and control of the electricity grid, and then systemic modelling as an aid to decision-making on investments.

The question of flexibility requirements is a global issue, as pointed out by the International Energy Agency (IEA). Nevertheless, the national challenges are high, and our economic and strategic position is at stake. Some maintain that the issue is not urgent. **Such an attitude overlooks the synchronous grid of continental Europe, which from 2022 onwards, will make us vulnerable to the impact of decommissioning of nuclear and coal power stations in neighbouring countries. Nor does it take into account the time required to prepare the renewal of the nuclear fleet,** bearing in mind that while the share of dispatchable nuclear power stations is decreasing, they play a key role in balancing the network.

This report sets out potential solutions to ensure flexibility, highlighting the problems to resolve before implementing them, and the research needed to do so.

Flexibility solutions

The main solutions involve adjustment of production, interconnection of grids, storage, and demand flexibility.

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French nuclear power stations were designed to be adjustable, and any future generations should take the same approach.
Long-distance interconnection, although a powerful means of compensating meteorological fluctuations, comes up against the difficulty of acquiring social acceptance of new high-voltage overhead lines and the high cost of underground lines.

Storage ranging from a few hours to several days benefits from the spectacular drop in the cost of batteries resulting from the growth of the electric vehicle market. Lithium-ion is by far the leading sector, although other options are under exploration. These batteries can also tackle the problem of maintaining voltage and frequency (grid support and grid forming). Electric vehicle batteries can be used as a backup (known as vehicle-to-grid), provided that exchange services are developed between parking places and consumption requirements. But in that case, who would pay for the two-way interface between the car and the grid? This is one of the economic issues raised by flexibility equipment and services.

Long-term storage (several weeks to several months), which is necessary to compensate for sporadic drop-outs of intermittent RE, has no viable economic solution up to the 2035 horizon. Currently, the only operational solutions are hydroelectric dams with pumped energy transfer stations (STEPs), but there is little potential to develop these in Europe due to a lack of new sites acceptable to civil society. This critical problem is a strong motivation for research, in particular on technologies like hydrogen.

Demand response management is a long-standing practice with industrial consumers, in particular electricity-intensive manufacturers. Going further than the 5GW currently estimated would involve the "flexi-design" of installations in order to maintain production despite power interruptions. But once again, how would this investment be financed?

For private individuals, **residential demand response management** is starting to emerge in solutions put forward by aggregators, facilitated by digital interfaces. Demand response and the supply of services to the grid generated by this flexibility are an example of the new services opened up by digital technology, bearing in mind that reliability is essential because grid operations must not be jeopardized.

Digital technology is central to the development of flexibility. Using sensors and transmission tools, digital technology brings operators detailed knowledge of the state of the grid. Thanks to processing capacities and diverse actuators (often in the form of powerful electronic equipment), operators can react in real time, regulate power injection and outage conditions, and anticipate short circuits.

Although the grid is now open to a wide range of actors, the system needs to be managed as a coherent whole, with an architecture adapted to decentralized intelligent dispatch and control. The most complex part is **power distribution,** involving several operators and direct contact with millions of users. While self-consumption brings benefits for users, local loops do not have electric flexibility reserves, which would guarantee security of supply and the quality of the current: connection to the grid remains an indispensable security for consumers. However, the present pricing of transmission (in France, TURPE2), featuring 80% energy and 20% power, does not reflect its real cost.

The decentralization of the grid, the multiplication of injection points, and the arrival of new services open up new opportunities. However, they bring the risk of foreign operators accessing data that captures value, and of cyber-attacks, both of which call for protection.

Many of these questions require modelling. Models and digital technology are interlinked, due to the means of calculation employed and the rising use of increasingly high volumes of data in models. These models will need to be built in a systemic perspective and cover technical, economic and social aspects, while considering new uncertainties related to RE forecasting and user behaviour.

Models can help to structure markets and provide them with appropriate operating rules. The current markets were set up to improve the instantaneous use of the means available. **They do not give out price signals that are likely to encourage long-term investments.** However, the market is a tool to give value to flexibility, provided that the different services are clearly defined, and bearing in mind that the remuneration will depend on the pricing.

Research priorities

Our analyses lead us to recommend the following themes, in agreement with the ANCRE[3] alliance: **digital solutions** (decentralization of control and dispatch, cyber-security, defence of value chains), **modulation of electricity production, interconnections, storage** (including combinations with other energy sources), **demand response, network reliability, modelling, and the economic and regulatory aspects of flexibility.**

We have given indications of the type of effort required, which depends on the issues, the maturity of the solutions, and French capacities: an industrialization problem does not call for the same treatment as an upstream research problem.

2. *Tarif d'utilisation des réseaux publics d'électricité* (public electricity grid user rate) aimed at remunerating the dispatch of electricity in terms of both transmission (high voltage) and distribution (mid and low voltage).

3. Alliance nationale de coordination de la recherche pour l'énergie (national alliance for energy research coordination)

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OBJECTIVES

This report presents the work pursued by ANRT over the last three years on the national energy research strategy. The working group initially defined **six alarm warnings and priorities to investigate in energy research (2018)**, before concentrating on the following two priorities: challenges relating to **modelling the electric power system (2019),** then those relating to **flexibility,** the subject of this report.

Following a general overview of the situation highlighting the sharp rise in the need for flexibility due to the introduction of renewable energy, this report describes the main challenges and presents possible solutions for achieving flexibility, analysing their potential and the conditions for producing and implementing them, for France in its European environment.

These conditions are not only technical, they are also economic, social, environmental and regulatory. The quality of electricity supply needs to be maintained, while tackling new security questions, in a system where electricity production sources are set to become increasingly numerous, decentralized, and often intermittent. This is all the more restricting given that electricity is not storable, unlike other types of energy (gas, oil, coal): electricity production must be equal to its consumption, at all times. The conventional means of producing energy correspond to different forms of energy storage[4], but electricity storage requires conversion into a form of storable energy whose capacities are currently limited with timescales that rarely exceed a week[5]. In addition, it remains to be determined who will shoulder the considerable investment costs, even though one of the goals of flexibility is specifically to bring these down. But is it really possible to achieve everything at once?

We have attempted to highlight the corresponding problems and then translate them into needs and research priorities.

Given the high number of interactions, the challenges and components of flexibility can only be easily understood by taking a systemic perspective. This was a constant preoccupation for the group, illustrated by the diversity of its participants and their interventions.

The report concludes with recommendations addressed to public authorities, public research bodies and companies.

It includes an annex setting out the vision of the ANCRE alliance that took part in the group's work. The report is partly inspired by this vision, although without sharing the hope that by 2035 hydrogen might provide an economically viable solution for inter-seasonal storage, mostly because of the absence of economic models to deploy technical solutions[6]. This major problem remains unresolved.

Given the considerable growth of digital technology, a second annex presents the keys to how it can help provide flexibility.

4- Fuel in reactors for nuclear energy, stored water for hydropower, storage of fossil fuels like coal/gas/oil products, storage of biomass, chemical storage for batteries, hydrogen storage for fuel cells, heat, etc.

5- No really viable solution currently exists for the inter-seasonal storage of electricity, except for pumped energy transfer stations located on high dams. In addition, electricity storage requires being able to release this electricity in the same form: the fact of converting, for example, excess renewable electricity into an intermediate storable form (potential, kinetic, chemical, thermal energy, etc.) only amounts to storage if the energy thus transformed can be converted back into electricity later and reused in this form at a different time.

6- The Académie des Technologies, in its July 2020 report, sets out the role of hydrogen in establishing a low-carbon economy and provides recommendations for hydrogen's positive contribution to the ecological transition through the development of an industrial sector. Download the report at http://academie-technologies-prod.s3.amazonaws.com/2020/12/10/14/00/10/ec136763-95ea-409d-92de- 4a7d3acb437e/201203%20Hydroge%C-C%80ne%20web%20V5%20cdef.pdf»

1 GENERAL SITUATION
FLEXIBILITY REQUIREMENTS IN THE FRENCH AND EUROPEAN ELECTRIC POWER SYSTEM

1.1 GLOBAL AND EUROPEAN ENERGY MIX SUBJECT TO EXTENSIVE REORGANIZATION

The debates on flexibility requirements in the electric power system are numerous and bring a whole range of stakeholders into play. Flexibility can be defined as the intentional adjustment of power at one or more sites, upwards or downwards, by injection or withdrawal, actively or reactively, during a given period, and as a reaction to an outside signal to provide a service[7]. This report selects three electric power system requirements that flexibility attempts to respond to[8]:

(i) Adjustment (daily, weekly, monthly) of demand;
(ii) Variability of supply, which becomes greater with the increasing share of RE in electricity production;

(iii) Robustness of the system in case of unexpected outside events (weather conditions) or inside events (unexpected production shortages).

These requirements regularly include achieving a balance between production and consumption: the electricity system must be capable of matching electricity supply with demand, at all times. This balance needs to be obtained in the best operating, cost and acceptability conditions.

However, these conditions change dramatically with the increased proportion of intermittent renewable energy: in practice, electricity generated from wind or solar power. The availability of these types of power does not depend on humans, but on nature: they are fluctuating and partly unpredictable. This leads to a considerable increase in flexibility, amplitude and frequency requirements.

In variable conditions depending on the country, this is a global phenomenon, since both of these energy sources have the advantage of being autonomous and of not directly emitting CO2. While coal is currently the primary source of electricity production, IEA forecasts anticipate that in 2040 almost half of the electricity in the world will come from solar and wind power, in a context where electricity consumption is currently growing at over 2% per year, and where 90% of future needs will come from developing countries.

The transformation of the European electric power system began nearly two decades ago, accelerated by the urgent need to combat climate change. Apart from the growing penetration of RE, the objective is to improve energy efficiency and manage energy demand[9], while the integration of digital technology should enable the control of more decentralized electricity networks and the establishment of interfaces with consumers.

These technological shifts are accompanied by considerable political, economic, environmental and regulatory developments: the opening up of electricity markets starting at the end of the 1990s generating new competition and new stakeholder interplay; reconfiguration of market structures that now have to integrate technological innovations as well as the growth

7- Official definition by the French electricity company Enedis (translation).
8- Source: RTE forecast balance (2017).
9- Action plan adopted in December 2008 last revised in June 2019 by the European Union (Clean Energy Package), with targets of -40% greenhouse gas emissions, +32% renewable energy in the energy mix, and +32.5% energy savings by 2030 compared to 1990. In December 2020, given the requirements of the Paris Agreement to periodically upscale its ambitions, the European Council approved a new emissions reduction target for 2030 involving a net reduction in greenhouse gas emissions in the EU of at least 55% by 2030 compared to 1990 levels. It invites co-legislators to take this new objective into account in the draft European law on climate and to then rapidly adopt it.

of local citizens' initiatives[10]; the need to build and affirm a strong industrial position in the face of the United States and China; the size of investments; and a clear need to strengthen energy solidarity between interconnected countries.

These developments are reinforced by the European Green Deal, and at national level by the France Relance recovery plan, the green part of which is also supported by the EU budget[11].

However, the introduction into the European energy mix of intermittent RE, which is an economic priority in the merit order[12], not only generates a significant rise in flexibility requirements, but in the long term creates new challenges and specific infrastructure needs to ensure the operation of electrical systems, in other words, network stability, dispatchability and resilience[13].

Moreover, programming electricity production no longer simply involves adapting to a variable European demand, but also **monitoring the variation of RE production in an increasingly decentralized system.** In addition, this issue highlights a new dimension of flexibility at the level of the distribution networks, which connect almost all intermittent RE and now have to manage both withdrawal and injection congestions. Distribution networks thus represent a critical issue for the energy transition today: the role played by distribution system operators (DSOs) is thus no longer restricted to connecting customers, controlling infrastructures, ensuring the operation of the network, and carrying out metering. It also involves anticipating and integrating all of the technological, economic and social breakthroughs that characterize the transition and occur at an increasingly decentralized level: these obviously include variable RE, but also charging facilities for electric vehicles, individual and collective self-consumption, reaction to energy data at shorter timescales, and support for local energy initiatives that must imperatively interconnect with the national electricity grid in order not to impede its functioning. DSOs thus become distribution system managers[14].

Nevertheless, the existence of periods of low RE production can make it necessary to mobilize almost all of the thermal production means in order to meet demand, such as in winter at peak consumption periods. On the other hand, we might imagine that the increasing development of variable RE will mean that installed capacities will be able to meet total demand in some regions and at certain times of year (e.g. in summer)[15]. If so, once the maximum export capacity has been reached in the interconnections, there is a risk of congestion on the grid, and balancing the system by capping the excess RE supply will probably prove insufficient. It may then be necessary to take the preventative measure of interrupting the production of incidental RE in order to dispose of the necessary means to ensure load following or to provide sufficient inertia for the stability of the system. In the European system, this RE variability is currently mainly compensated by conventional means of production, many of which rely on fossil fuels.

1.2
THE FRENCH SITUATION

1.2.1 Important short-term decisions to sustain the future of energy post-2035

In France, the multi-annual energy plan (*programmation pluriannuelle de l'énergie - PPE*)

10- For example, in the process of reforming electricity pricing faced with rising numbers of consumers and local energy communities.
11- In late 2019, the Green Deal suggested raising the greenhouse gas emissions reduction threshold from -40% to -55% by 2030. In September 2020, the French economic recovery plan devoted almost 30 billion euros to green projects of which about 19 billion from EU funds.
12- The merit order is the principle of an economic precedence of electricity production means, consisting in primarily employing production sources with the cheapest variable marginal cost. In France, this concerns intermittent RE (solar, wind), followed by hydropower, nuclear, and thermal (gas, fuel oil). Note that lake hydropower depends on use value and covers both peak-load and middle-load demand.
13- These requirements can be observed starting from some thresholds of variable RE capacities linked up to the grid and depend on the existing production mix, both on the supply and demand sides. In France for example, requirements are likely to evolve according to the share of nuclear in the mix in the long term: the smaller this share of nuclear energy, the greater the share of comparatively less dispatchable RE, which will have an impact on the behaviour of the system and the resilience of networks.
14- The term distribution system manager is frequently employed in Europe to underline the changing occupation of distribution system operators due to local issues related to the energy and digital transition, with a view to accompanying the electric power system as a whole.
15- A degree of caution should however be maintained regarding the social appetite for striking a local balance between production and consumption. This balance represents a constraint that could destroy the collective value from the point of view of the electric power system, because the overall optimum of the system is always greater than the sum of local optimums.

anticipates a 17% to 40% increase of RE in the mix by 2030, resulting in a 50% decrease in the share of nuclear by 2035. If developments in the power system follow the path set out in the current PPE (2023-2028) and the different scenarios produced by RTE up to 2035, the French electricity system should, thanks to nuclear and gravitational power plants, be able to meet flexibility requirements up to that date, without emitting more CO_2[16]. **If, after 2035, the proportion of nuclear energy drops further, in a situation where numerous conventional European production means will no longer be available[17], achieving this target would be more difficult, due to the unfortunately likely absence of inter-seasonal electricity storage at an acceptable cost.** The decision whether to establish a rejuvenated fleet of nuclear power stations in 2035 should be made in the near future, before the next PPE (i.e. by 2022-2023), which leaves little time to investigate this question of target production mix and the flexibility that could be associated with it in the coming three decades. A work programme, set out in the PPE adopted in April 2020, has been launched to study different scenarios, some of which include the construction of new nuclear plants, while others feature high levels of renewable energy.

Also starting in 2022, strong perturbations can be expected in the European electricity mix due to the closure of dispatchable plants (German nuclear power stations, and most coal-fired power stations). These closures risk accentuating the pressure on security of supply by the end of 2022. The government will need to step up its vigilance and rapidly define a roadmap and priorities for flexibility in terms of research investment, equipment and production[18].

1.2.2 Other issues

Security of supply

The current energy transition and the growth in new electricity usages (electric mobility, mass connected equipment, etc.) makes it all the more essential to ensure long-term energy supply that corresponds to the quantity of electricity consumed at any moment. Guaranteeing the supply of electricity thus requires making electricity available to everyone at all times, and the deployment of flexibility should start by addressing this indispensable issue.

Reduction of CO2 emissions

In its current state, **French electricity production has one of the lowest carbon levels in Europe.** The country does however use fossil-fuel power stations to deal with peak demand. Flexibility in the power system would not only ensure the efficient insertion of intermittent RE into the network, it would reduce these peaks by managing consumption, and develop complementary services that decrease the carbon footprint.

One example is V2G, an emerging solution that will in the long term be capable of sending electricity back into the grid. The benefits are twofold: electric vehicles reduce the carbon footprint of mobility while supplying additional flexibility thanks to the stationary storage provided by their batteries.

Lastly, we should not forget research on deploying Power-to-X, hydrogen, and more generally all technologies that involve converting electricity of renewable origin into reusable energy (e.g. by electrolysis), provided that the conversion systems used have limited carbon content and grey energy.

Local management of the supply-demand balance

The electric power system will evolve from a state in which, until recently, dispatching was almost exclusively operated through centralized production groups, to a state in which this dispatching will need to be spread out in a much more decentralized manner throughout the grid, and in particular distribution infrastructures, to which almost 90% of intermittent RE is linked up. This paradigm shift will require dynamic management of the much more complex supply-demand balance, along with stronger requirements for information systems and technologies, bearing in mind that rudimentary technologies like those used to control water heaters can still be very useful to manage the supply-demand balance.

16- Ce point est particulièrement important compte tenu des polémiques récentes sur l'arrêt du gaz naturel dans les logements neufs. Voir rapport de RTE sur l'évaluation de scénarios possibles pour décarboner le chauffage dans le secteur du bâtiment à l'horizon 2035. https://www.rte-france.com/actualites/evaluation-de-scenarios-possibles-pour-decarboner-le-chauffage-dans-le-secteur-du»

17- Fermeture des centrales nucléaires en Allemagne d'ici 2022, et fermeture des centrales à charbon en France (2022), en Allemagne (2038), et en Pologne (2049).

18- La notion de sécurité d'approvisionnement, telle que définie par les pouvoirs publics français, renvoie à une durée moyenne de défaillance maximale, c'est-à-dire une durée pendant laquelle l'équilibre offre-demande ne peut pas être assuré par les marchés de l'électricité dans toutes les configurations modélisées par le gestionnaire du réseau de transport. Cette durée moyenne doit être inférieure ou égale à trois heures par an. Le risque sur la sécurité d'approvisionnement renvoie donc à une situation d'exploitation dégradée mais maîtrisée du système électrique. Ce risque doit être impérativement distingué d'une situation de black-out, qui implique une perte généralisée de l'alimentation électrique sur le territoire.

Voltage and frequency control

Concerning the stability of the system, RE is currently connected up to the grid through power electronics interfaces, which can lead to a drop in inertia in the grid and raise the question of frequency and voltage regulation. In the current state of deployment, some European electric power systems that have a high share of variable RE practise preventive production capping[19]. This system allows them to maintain a sufficient number of machines running on the grid, and therefore a minimum inertia level to avoid a drop in voltage and frequency. Since managing the inertia in the system is a key problem for operation, the use of flexibility could result in improved recovery of the renewable yield.

Minimization of investment and operating costs

The development of flexibility[20] in the electric power system will require considerable investments concerning both the supply-demand balance for the system and the electricity grid (e.g. reinforcement of installations to avoid network congestions). While some of these investments could be compensated by the costs avoided in production capacities, their technological orientations will be recommended by public authorities, and their finance conditions will be affected by the energy markets and resulting price signals. Flexibility that is incorrectly calibrated can lead to over-investment in production and storage equipment[21], which creates a burden on the public budget, consumers and companies, with repercussions on the domestic balance of payments, concerning both energy imports and a loss of export competitiveness. In contrast, the correct calibration of flexibility integrates the cost of investments, operating costs, the cost of flexibility, and the level of service expected from the electric power system (non-distributed energy and non-injected energy). In fact, flexibility has a cost, comprising the cost of smart equipment for control and connection (and the energy it consumes), and the cost of storage, without forgetting the "social cost" connected to changing behaviour. However, the avoided costs should also be quantified. This coverage of the overall cost of flexibility raises two problems:

- First, **the capacity of signals from the established energy market, which only give very short-term indications,** providing little encouragement for heavy, long-term investments. Nevertheless, recent initiatives, like the establishment of a capacity mechanism since January 2017, constitute an initial response to these issues, in particular via the multi-annual income security measure for new investments, bringing the hope of a progressive move towards more long-term market signals.
- Second, the distribution of costs and remuneration between equipment manufacturers, production and distribution operators, service providers, and users.

Weak price signals on markets

Currently, **the increased injection of renewable, non-dispatchable electricity is bringing down the price of electricity on wholesale markets.** Although intermittent RE is not generally subject to the economic consequences of this drop because of the support it receives from the state (subsidies, advantageous feed-in tariffs, tax breaks, etc.), other investments are impacted strongly, in line with national and European RE development objectives. At the present market price, very few new investments are profitable, all the more so in a system in which more and more capacities have high fixed costs and low or almost-nil variable costs. The massive injection of RE, which will technically require increasing flexibility to adjust supply to demand, assumes that flexibility has a value, and therefore a price. **Yet the current market prices do not allow stakeholders to launch into credible investments with high capital value, which risks hindering the deployment of flexibility.** The establishment of a mechanism in 2015 to remunerate flexibility (block exchange notification of demand response - NEBEF) has enabled a dozen actors to gain a foothold on day-ahead energy markets. However, regular calls for tender for demand-response solutions illustrate the need to promote these solutions in the energy mix. Similarly, the capacity mechanism mentioned above aims to direct investments towards longer-term market signals, even though the effects will probably be progressive.

19- Preventive production capping consists in intentionally limiting the power of available intermittent RE injected into the grid and economically incentivized by an obligation to purchase this RE. This restriction aims to prevent the risk of congestion and unbalanced supply-demand, e.g. in a situation of surplus RE production compared to demand.
20- Flexibility should be supplied by production means or usages, and exceptionally by specific means (e.g. primary frequency control provided by batteries), or even smart grids. The idea is therefore to develop flexibility so as to avoid having to develop specific flexibility.
21- For some technologies, like batteries, this should also include the cost of components' ageing due to cycling.

The economic valuation of flexibility, at its right price and reflecting the services that it will provide to the system, will therefore need to provide an incentive for investments, not just in the different production means that will make up tomorrow's energy mix, but in innovation (electric vehicles, demand-response or dispatch mechanisms, storage, etc.), which will provide the system with the required flexibility.

Social issues

The deployment of some types of renewable energy (e.g. onshore wind power), storage technologies (e.g. batteries, hydrogen, etc.), and electrical interconnections requires acceptation by local inhabitants, who are increasingly concerned by the impact of these innovations on their territory: environmental impacts related to the use of some materials and recovery or storage problems for waste at end of life; social impacts of integrating RE into the landscape, and on land planning and buildings; impacts on the local biosphere (fauna and flora); possible health impacts on residents living close to installations, etc. Developers of innovative solutions must imperatively minimize the risk generated by their technologies for inhabitants in order to improve their acceptability and create a climate of social trust.

Overall, the development of flexibilities will also require new exchanges, new positioning, new partnerships, and new skills in an energy landscape where Europe faces major international powers armed with cutting-edge technology, such as the United States and China.

2 POTENTIAL SOURCES OF FLEXIBILITY

The multiple sources of flexibility involve: production adjustment, interconnections, storage technologies, implicit or explicit demand response, and production and consumption forecasts at different time horizons.

2.1 PRODUCTION ADJUSTMENT

The first level of flexibility in the electric power system is ensured by **conventional production means** as featured in the merit order, ranked by increasing marginal variable cost: hydropower, nuclear, coal, combined-cycle gas plants, combined-cycle gas turbine power plants (CCGTs). The profiles of these means are different from those of RE production, and they contribute to the security of the system in the face of RE variability. Unlike in other countries (e.g. Ukraine), **French nuclear power stations were designed to be adjustable,** while being employed as a basic means of electricity production[22]. They are therefore a strong asset in the integration of RE.

Nevertheless, it is important to point out the significant loss of earnings related to load-following nuclear power in France[23]: this could have an eviction effect, and reduce the injection of dispatchable nuclear energy into the system. It may in fact be preferable to maintain a high load factor and employ more alternative means of flexibility (like gas plants[24]) rather than stop nuclear power stations for several hours per day or week. The answer will depend on several parameters, such as the price of coal or the nature of demand related to the employment of basic production means[25]. It will have consequences on the sizing of the nuclear fleet, or the prolongation of the existing fleet, and possible reinforcements of the transmission and distribution networks.

2.2 INTERCONNECTIONS

In Europe, RE fluctuations are partially compensated from one zone to another by the effect of scattered load balancing on transmission networks. **The interconnection of networks is therefore a means of flexibility.** This is a crucial issue, even in regions of the same country, and between different EU Member States, depending on the profiles of their respective consumers and their production capacities. This possibility is reinforced from an economic point of view by market-coupling mechanisms put in place between several European states, which aim to guarantee the good usage of these interconnections by transmitting electricity from where it is cheapest to where it is most expensive. Limitations are due to social factors, involving action to hold back the installation of high-voltage lines everywhere. Germany, despite a considerable need to connect wind farms in the North Sea to its Bavarian factories, only succeeded in building 36 km of high-voltage lines in 2019.

However, although international interconnections represent undeniable assets for the flexibility and stability of the European electric power system, they will not be able to resolve all of the problems related to choices without a concertation on the mix of interconnected countries. On the other hand, their development necessarily involves questions of balancing and operating the network, which will need to be analysed at a much greater scale: the issue of flexibility must therefore be tackled at a supranational level.

22- Historically, nuclear power stations were designed to ensure supply continuously, and at the same time to respond to a drop in demand in off-peak periods, like at night: from the outset, they were devised so that their power could be rapidly diminished if necessary. However, some technical and economic limitations exist concerning the use of nuclear power for flexibility, i.e. the need for a minimum start-up and operating power for the stations, and the fact that it is more profitable to keep reactors running at full power.
23- Currently, over 50% to 60% of the French nuclear fleet automatically generates load following, while in other countries with a nuclear-based energy mix, fleets always operate at their nominal point, in order to extend the lifespan of the vessels (problem of variation in neutron bombardment) and reduce corrosion.
24- Note that gas-fired power plants are nevertheless employed after nuclear plants in the merit order. In terms of optimizing the mix, the relative competitiveness of nuclear and gas-fired power stations for different usage durations depends on the price of gas and CO_2.
25- In fact, for the electricity-intensive manufacturing sector, not maximizing the yield of a low-carbon means of production like nuclear can have a negative impact on both France's carbon footprint and on the opportunity to make competitive quantities available to encourage electricity-intensive companies to start or accelerate the decarbonization of their processes.

2.3 STORAGE

Storage solutions are mostly characterized by the following parameters:

- Energy capacity and retention duration
- Charging and discharging time
- Response time and power
- Conversion efficiency
- Environmental impact
- Technological maturity
- Cost.

The potential of the diverse solutions is illustrated in the following figures. For the storage of large quantities of energy for long durations, one solution stands out, i.e. pumped energy transfer stations (STEPs). Unfortunately, these stations are limited by geographical constraints and the refusal to see land flooded by water reservoirs. Demand-side flexibility is also provided by domestic hot water tanks, whose potential is currently estimated at about 4 GW[26].

One of the few remarkable recent inventions is the mass, low-cost production of lithium-ion batteries, initially for electric cars, but also to level out RE fluctuations or maintain the line frequency, despite the drop in inertia associated with the smaller proportion of rotor generators.

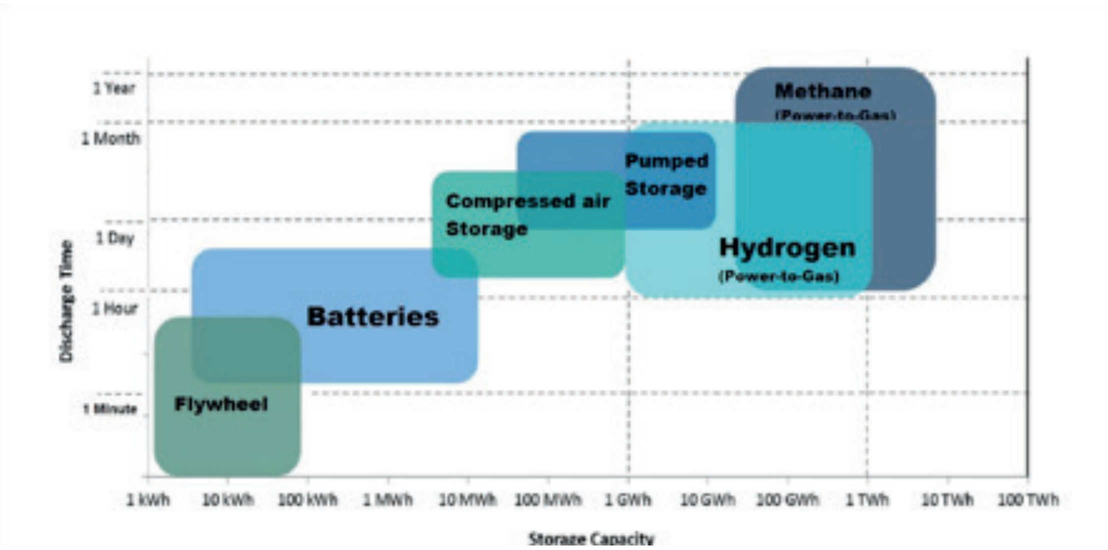

Figure 1 :

Comparison of different storage technologies according to their capacity and discharge time (autonomy)

Source : School of Engineering, RMIT University (2015)

This graph illustrates the importance of intensifying research on inter-seasonal storage. Battery-type technologies cannot store a very large amount of electricity, and they are devised for short-term use. On the other hand, hydrogen and power-to-methane, despite offering much greater storage capacities with longer autonomy, are still relatively costly and will require business models if they are to be profitable in the long term and considered as viable inter-seasonable storage means[27].

26- Source: working document on the definition of hypotheses on sources of demand-side flexibility, produced by the RTE "Flexibility" working group.
27- The Académie des Technologies, in its July 2020 report, sets out the role of hydrogen in putting into place a low-carbon economy and provides recommendations for hydrogen's positive contribution to the ecological transition through the development of an industrial sector. Download the report (in French) from: http://academie-technologies-prod.s3.amazonaws.com/2020/12/10/14/00/10/ec136763-95ea-409d-92de-4a7d3acb437e/201203%20Hydroge%C-C%80ne%20 web%20V5%20cdef.pdf»

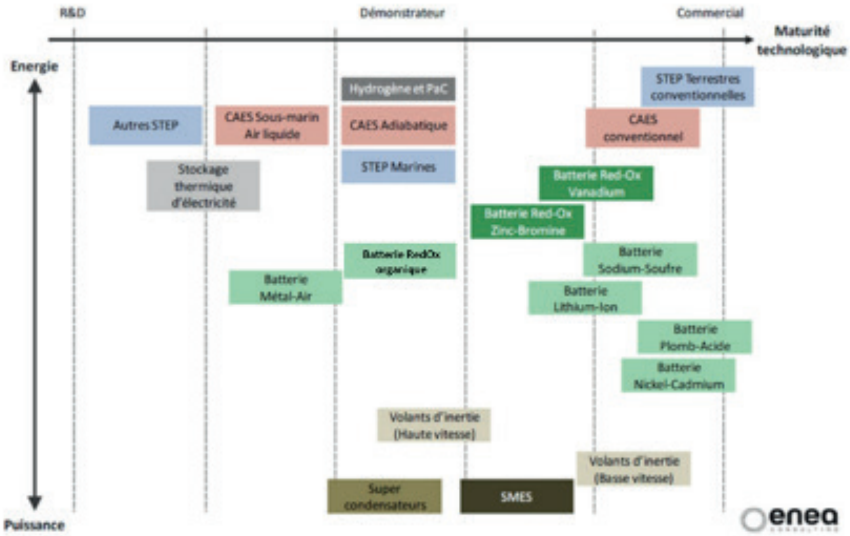

Figure 2 :

Level of technological maturity of the different means of electricity storage

Source: CRE and Enea Consulting

Storage and energy technologies have very different maturity levels: the most commercially mature technologies with high energy/power ratios are onshore STEPs, compressed-air storage and batteries. The TRL[28] of hydrogen-type technologies is still at demonstrator level.

Financial uncertainties regarding costs

Along with these technical and environmental criteria, still subject to significant uncertainties, comes a financial question, which is the cost of industrializing these technologies. While the cost of storage technologies is likely to drop considerably by 2030 – up to 70% on average for some technologies according to studies by the World Energy Council[29] – the notion of levelized cost of energy (LCOE[30]) is currently useful but inadequate. A comparison of the levelized cost of storage technologies is often restricted to observing only the technology in its primary storage function. This vision is inadequate because it does not take into account the specific situations in which the storage will be used, e.g. in association or in synergy with a photovoltaic solar production system (PV).

The levelized cost of this storage with or without association with a PV system will thus be very different, since the presence of this kind of synergy tends to increase the acceptable costs of storage.

In addition, the use of the same storage device for several applications (arbitrage, charge transfer, frequency control, etc.) also tends to bring down its levelized costs. The cumulation of applications is a trend that is worth considering and that is appearing on some markets (United States, Australia, etc.). This raises the question of rivalry between applications and the ownership of devices capable of providing different services.

28- Technology readiness level.
29- Source: Shifting from Cost to Value, report, World Energy Council, 2016.
30- Note that for storage, we talk of LCOS (levelized cost of storage).

Electrical mobility

In addition to stationary storage, the development of flexibility enabled by electrical mobility and vehicle batteries needs to tackle two problems: demand management, which contributes to avoiding consumption peaks, and the smoothing of RE production. In this area, the deployment of electric vehicles will bring several levels of flexibility:

- Smart charging, which consists in choosing the charging time in order to move the load and smooth out the consumption curve.
- Vehicle-to-home (V2H), which consists in smoothing domestic consumption more and providing emergency supply.
- V2G, which consists in sending electricity back into the grid and creating economic value by providing a form of incidental storage to the system without having to invest in additional stationary storage. However, the business model behind V2G remains to be seen: who will pay the additional cost of the interface between the car and the grid, in the car, and in the home? And what about the accelerated ageing of batteries beyond their primary mobility usage?

The storage valuation problem

Moreover, depending on the type of service provided by storage, the value created for the system will be different: storage can also avoid investments in reinforcing network infrastructures, or inserting variable RE production, or improving ways of tackling the uncertainties of supply-demand balance forecasts for network operators. For local authorities, the value of storage lies in its capacity to reduce the carbon content of their fleets thanks to electric vehicle batteries. For the producers of dispatchable means, storage is a means of choosing (between the fact of producing or instead storing) and can improve the performance of the system from an operational and environmental point of view. Lastly, for producers of variable RE, storage facilitates the anticipation of any regulatory constraints, such as obligations to consolidate the installed capacities in order to better participate in calls for tender on energy markets and optimize their selling price.

Lastly, the development of storage to provide flexibility in the grid will depend on parameters like the **price signals sent out by the market** to stimulate investments in certain technologies, and also on the **regulatory and normative power of French and European authorities,** and the framework that they will define in terms of **technological and environmental standards, taxation and support mechanisms** (e.g. subsidies for RE, incentivizing feed-back tariffs, combustion vehicle circulation quotas, etc.). At the European level, the regulatory framework will remain crucial in the short term, for example because the EU prohibits some stakeholders like system managers from becoming storage operators.

When it requires considerable investment, storage does not escape the difficulty that **price signals are too short term and too partial to provide incentives.** Moreover, it is important to avoid establishing overly excessive production capacities, because the value of storage assumes a degree of rarity. The value harnessed for the primary reserve, currently highly lucrative, can be provided by electro-chemical storage, but it is restricted to a very low level of consumption[31]. Too much storage would dilute the current value. In France, **the capacity mechanism** – and in particular its multi-annual remuneration measure for new investments – is designed to make up at least part of the lack of long-term signals[32].

Lastly, one way to reduce electricity storage requirements would be to envisage situations in which not all final uses would be electrified. Strategies aimed at storing renewable electricity in summer and consuming it in the form of low-carbon gas or heat in the winter could be envisaged for some specific applications. Similarly, intensifying energy-saving efforts would be a way of limiting – all things being equal elsewhere – the electrification of demand and thus electricity storage requirements.

31- About 1% according to ADEME.
32- Over 300 MW of batteries currently benefit from this measure and will be put into service in the next few years according to RTE.

2.4

DEMAND RESPONSE MANAGEMENT

Demand response, which is particularly developed in Europe at the industrial level[33], involves **temporarily reducing the physical consumption of a site or a group of given sites in the case of a sudden imbalance between electricity supply and demand.** The action is implemented in response to an external signal, for example during a peak consumption period. From a technical point of view, the demand response mechanism can be compared to a substitution of the means of electricity production that, in the absence of such a mechanism, would be employed to meet demand. It can be explicit, comprising an external action carried out on the consumer side (often by an aggregator) or implicit, in the form of a tariff incentive to consume at different times (in accordance with the pricing established by the energy provider).

Nevertheless, while demand response represents a considerable strong point for the electric power system from a techno-economic point of view, it is vital to reinforce basic **cybersecurity:** the use of protocols to effectively encrypt consumption, protection of consumer data recuperated by sensors against intrusions or hacking of erasable equipment. Note that consumption reduction objectives also take the form of programmes aimed at improved **demand dispatch,** which in turn generates flexibility: consuming less thus also means consuming better, which makes the load more manageable.

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"Electricity-intensive" industries[34]

Industrial demand response has significant potential for flexibility, with a basic consumption profile that can provide stability to the French grid at energy consumption peaks. Over the last few years, French industry has developed a mature demand response system, with a potential of around 5 GW, only 2.5 GW of which were used in 2020 according to ADEME. But going further can involve high costs: in major industrial processes, the quality of the service provided depends on the power made available at a given point in time. Some machines are not designed for a sudden, rapid interruption in their load, with a non-negligible risk for the production process when they start up again. Designers of electricity-intensive equipment must therefore make their tools more flexible ("flexi-design" concept) in order to respond when needed while guaranteeing operations (performance, reliability and operability).

Individual consumers

Explicit demand response is based on a contract between the operator and its final customers, and aims to remotely control the consumption of apparatus that have substantial, flexible, remotely controllable loads (e.g. heating, heat pumps, water heaters, electric vehicles via V2G). At the same time, this control does not have an impact on customers' usage provided it does not exceed a range of several dozen minutes for thermal uses.

Another pertinent form of electric demand response that does not reduce heating comfort for individuals is hybrid heat pumps (HP), which combine a small electric HP with a gas condensation or fuel oil boiler and a control system. The RTE/ADEME study on the electrification of heating by 2035 published in December 2020[35] indicates that the installation of 1 million hybrid HPs to replace electric HPs should reduce the electricity peak by 1.4 GW, without increasing CO2 emissions or the cost of investment for households if mains gas already exists.

Lastly, tariff response, known as "demand response indissociable from supply" or time-of use tariffs, is based on different tariffs for different consumption periods[36], and encourages consumers to adapt their behaviour in consequence, e.g. by postponing their consumption to a time when the price is lower.

Benefits for consumers

The benefits of demand response for consumers currently take the form of a double approach that controls both energy and consumption. In fact, demand response can lead to a deferral of

33- Industrial consumers currently play a major role in demand response compared to tertiary and residential consumers. Yet although residential demand response is currently less employed than industrial demand response, its potential is high (about 15 to 20 GW in France according to estimations by the aggregator Voltalis).
34- Although demand response is illustrated here by the case of electricity-intensive industries, small and mid-sized enterprises are also important, along with local authorities, whose demand flexibility should indispensably be considered.
35- See the RTE report (in French) evaluating possible scenarios to reduce carbon emissions from heating in the building sector by 2035 (December 2020). Downloadable (in French) at: https://www.rte-france.com/actualites/evaluation-de-scenarios-possibles-pour-decarboner-le-chauffage-dans-le-secteur-du»
36- This is for example the case for peak/off-peak tariffs.

energy consumption. Installing connected digital boxes in some households allows for close control of equipment by a demand-response operator and real-time tracking of the consumption of controlled electric apparatus, which can lead to more virtuous, lower consumption patterns.

Benefits for the electric power system

For the power system, dispatching of the load by demand-response operators usually involves employing smart algorithms and offers numerous solutions ranging from real time to long term: very fast adjustment services with very low capacity for transmission system operators in order to maintain the frequency at 50 Hz and therefore the supply-demand balance at all times (automatic primary reserve); sale of demand-response energy on the energy market (e.g. NEBEF mechanism); sale of power availability on the capacity market; or services to the distribution network to help resolve network constraint issues. It is also important to ensure that this coordinated dispatch, which perturbs the hypotheses of a natural *load-balancing* effect in sizing methods, does not create congestions that would not have existed without flexibility. The balancing blocks created by operators thus represent an alternative to production but also to investments on the network in terms of deployment, reinforcement, or long-term maintenance of installations[37].

Benefits for the community

In the context of the current energy mix, demand response is mainly employed to avoid conventional electricity production (mostly carbon-based in peak periods) and therefore to help reduce carbon emissions, provided that the deferred consumption does not take place during a high-carbon-based period. It can also be used to adapt consumption to intermittent production due to the massive integration of RE into the system, and therefore to shift and direct consumption to become more flexible and to adapt to the production available at the given moment. This effect will need to extend with the penetration of RE. It also represents a means to manage network flexibility on a local level, for example by developing tools for identifying demand-response consumption on a given geographic perimeter, and therefore triggering demand response if needed[38]. The issue of the reliability of demand response to a signal is all the more important when flexibility is expected locally; the regulation framework should provide an incentive and guarantee for this kind of reliability in the long term.

Lastly, from an economic point of view, the presence of demand response operators on the market will avoid peak consumption and therefore the production of expensive peak energy. This leads to a drop in market prices, which in turn generates savings for providers that obtain their supplies from wholesale markets: they will thus buy quantities of electricity at a comparatively cheaper price than if they had purchased it from peaking power plants.

More generally, in terms of evaluating the benefits for the community, the cost of demand response for users needs to be compared with the savings for the electric power system.

2.5 IMPROVED PRODUCTION AND CONSUMPTION FORECASTS

Although forecasts are not a means of flexibility, their improvement constitutes a lever that can act to reduce the overall cost of flexibility.

The increasing development of intermittent RE as a potential substitute for existing dispatchable production means, like nuclear or thermal power plants, raises the problem of predictability. Thus, the very seasonal production profile of wind turbines (which produce more energy in winter than in summer) can represent wide-ranging energy variations compared to European-level demand[39]. As a result, the increasing penetration of RE in the electric power system generates significantly higher risks in the form of lower **predictability** of annual demand, much less marked daily and weekly management cycles, and more extensive pressure periods in the system (e.g. winter demand peaks). Although the

37 -Note however that the development of decentralized storage and load dispatch to customers connected to the grid can also result in congestions on local networks.
38- Grids will mainly be subject to injection congestions, which involves establishing the symmetrical management of injection and withdrawal congestions.
39- The availability of intermittent RE nevertheless remains low: in France the average load rate of a wind turbine, which represents the relationship between the number of operating hours at nominal power of the turbine and the number of hours in a year, is about 20% to 25%. For solar panels, it is about 15%.

capacity to predict the production of variable RE in the short term (e.g. one day ahead) remains acceptable, beyond several days it relies on essentially probabilistic forecasting methods. An improved capacity to predict variable RE makes it easier for market players (producers, transmission and distribution network managers, etc.) to ensure a balance in the system in real time.

3 RESOURCES, SERVICES AND ADDITIONAL ISSUES

3.1 FLEXIBILITY DEVISED TO PROVIDE SERVICES TO THE GRID

Flexibility aimed at providing services to the grid can be grouped into three categories: flexibility related to **power control** (consumption and production); flexibility aimed at providing grid support; and flexibility aimed at providing synthetic inertia, called **grid forming**.

Flexibility related to power control includes, on the consumption side, **industrial and domestic loads** that are dispatchable and adjustable, **electric vehicles** (in particular V2G), and **stationary storage.** On the production side, it concerns totally or partially controllable production, such as variable RE, and stationary and mobile storage. This category of flexibility concerns transmission and distribution infrastructures, and ranges from the very short term to the long term.

Flexibility aimed at providing grid support assimilates usages with active and reactive power sources and acts on voltage and frequency control, which has to take place in real time. This type of flexibility concerns totally or partially controllable productions, and stationary and mobile storage. The question is to determine how this flexibility will be controlled in real time, or one day ahead, and to coordinate the services that these usages provide to the network in investment planning (production means, network infrastructure, etc.) in the long term.

Flexibility aimed at grid forming, which means injecting additional "synthetic" kinetic energy into the grid to limit frequency drops in real time, assimilates usages with controllable power sources that do not need a voltage reference and can be disconnected from the grid (e.g. microgrids). This essentially concerns means of production and storage associated with other types of flexibility to address grid services in real time.

3.2 THE IMPORTANCE OF SPATIAL AND TEMPORAL SCALES

The performances of these mechanisms will largely depend on the spatial and temporal scales on which they are implemented.

From a spatial point of view, the main challenge is to coordinate the services provided **from the individual and domestic usage level up to that of the European transmission network,** for example in balancing flows on the European mix interconnected via transborder electricity imports and exports. From a temporal point of view, this flexibility will need to coordinate the close mechanisms of real time, decisions whose impacts will extend over decades, and the intermediate timescales of forecast management for installations.

Challenges related to real time

Concerning real time and the imperative of ensuring the safety of people and equipment along with network stability, the main challenges concern:

- Managing inertia in networks, given that the increased power electronics associated with RE diminish the grid inertia while increasing the rate of change of frequency and voltage dips.
- The evolution of grid protection plans, mostly based on detecting short circuits in synchronous machines, and which become inoperative with a large penetration of power electronics. The revision of grid protection plans should thus adapt "in real time" to the activation of decentralized production/

storage (withdrawal/injection), and protect the power electronics interfaces, which are a lot more fragile than conventional rotor machines.
- The technical and economic effort required to manage the controllability and predictability of variable RE and to limit the uncertainty that it generates.

Challenges related to the short/mid term

Concerning forecast management in the short and mid terms, which involves day-ahead control mechanisms up to a minute scale for controlling the grid, the main challenges are the following:

- The residual uncertainty associated with the controllability and limited predictability of intermittent RE[40]. This challenge will be all the greater in non-interconnected zones (NIZs) such as islands, where the potential for deploying RE is high due to isolation and often carbon-based production mixes.
- The need for energy management systems[41] (EMS) to create synergies between several RE production systems and storage.
- The need for control algorithms to manage the variability of RE, with specific grid code situations and regulations in each country.

Challenges related to the long term

Lastly, concerning the long term and investment decisions, the main challenge will be to plan investments related to integrating RE and new usages (e.g. electric mobility) into grid infrastructures. The issues to solve will concern:

- Uncertainties related to forecasting RE production and demand, which increase beyond a period of several days, but decrease as the spatial scale extends due to the load-balancing effect.
- The integration of flexibility into investment decisions, with these models also coming up against a regulatory requirement that will need to be met. As an example, the 2019 Clean Energy Package (CEP) establishes a framework concerning access to flexibility services for network operators.
- The integration of socio-economic models and quantification of the risk associated with flexibility.
- The increasingly blurred line between the different scales of electrical networks (transmission, distribution) and the growing need for coordination between the operators of these infrastructures.

3.3 INVESTMENT PLANNING, STIMULATION OF PRIVATE INVESTMENT BY THE MARKET, AND THE ROLE OF ELECTRICITY PRICING IN THE DEPLOYMENT OF FLEXIBILITY

Potential investments to coordinate with markets

The opening up of the wholesale market to competition nearly 20 years ago has given rise to a multitude of production operators. Investments now depend on decisions made by increasingly numerous and decentralized stakeholders, based on their own anticipations, and need to be incentivized by price signals. Their profitability can evolve considerably depending on parameters like the volatility of markets, their liquidity, the occurrence of price peaks (difficult to anticipate), the regulatory risk, or changing prices for other fuels used to produce electricity (coal, gas, oil).

As a result, electricity market mechanisms have been set up to identify the best utilization of production means in the European mix, in order to allow the different producers to deal with consumption. Given the significant diversity of the variable costs of equipment, electricity prices remain highly sensitive to the consumption of customers (who are not involved in the wholesale market) and to the quantities offered by stakeholders, which themselves depend on uncertainties such as the degree of predictability of intermittent RE. The equilibrium price of electricity that forms on the market must remunerate all of the offers made by these stakeholders, which results in a profit for the most competitive means of production[42]. This profit must also be able to remunerate all of the loads of these assets. Yet in tense situations, for example demand peaks, comparatively more

40- Of course, the variability of renewable energy sources is not equal: apart from operating incidents, tides are predictable for tidal energy converters, and solar power is predictable during the night because production is nil. Run-of-river hydropower plants, wind and wave swell are partly predictable. However, solar energy is much less predictable during the day.
41- An energy management system, in the broad sense, involves a set of digital tools employed to survey, control, pilot and optimize the performances of an electric power system. At household scale, one of the applications is to manage local energy systems in order to optimize a decentralized production (like solar panels) for a usage such as an electric vehicle or a storage system (like a residential battery).
42- This involves the "inframarginal" rent for the means of electricity production with the lowest variable costs according to the merit order.

expensive means of production are solicited (thermal power stations).

Market imperfections and their consequences

In a hypothetically perfect market where consumers would be remunerated if they accepted to reduce their consumption at peak times, a natural balance would be struck through a voluntary demand response activated by the "last" consumers to be supplied. This mechanism would develop very high prices corresponding to the utility for consumers in these high-pressure situations, and would serve as a basis for producers to commit investments to the construction of new facilities. However, the market reality is different today: in practice, exchanges are established between suppliers following the mobilization of all means of production. The only solution for the transmission system operator is to launch load-shedding operations to reach a supply-demand balance during periods of extreme tension, which can concern all customers. In other words, **the current market mechanisms are widely oriented towards short-term decisions,** and the resulting electricity prices underline a crucial point, which is the question of **sizing the production fleet to handle demand peaks.** In France, recent solutions like the capacity mechanism and its multi-annual, contract-based measures constitute the first step towards resolving this problem, but their effects will need to be measured in the long term. The issue of the sizing of the production fleet remains a challenge and will determine the quality of the service for the community, the objective being to strike a balance between the costs involved in constructing state-of-the-art resources and the loss for the community associated with a fault in the grid.

In this context, the flexibility required to ensure stability of the network and the technical dispatching of the European electric power system, and guarantee optimal supply quality for all consumers, will only be available if its development is economically anticipated and coordinated for all time horizons and between all stakeholders. As a result, there is a real need to "programme" this development in order to implement solutions that will make it possible to integrate more intermittent RE into the European system[43], at a lower cost and with reduced emissions. The integration of this RE and the reduced call for thermal energy will be reflected in the costs, which will be increasingly fixed. The question is therefore to determine:

- On the one hand, how to finance these investment costs in the long term. In fact, on the short-term market, electricity prices tend to go down, and market signals only give indications on a time scale of a few days, which will not motivate large, long-term investments.
- On the other hand, how to find levers that boost flexibility in order to encourage the different production means – including intermittent RE – to provide the system with the required flexibility.

The greater the penetration rate of RE in the mix, the greater the risk that its economic value on electricity markets will drop, and this decrease in the value cannot only be compensated by an increase in exogenous parameters such as the carbon price.

Necessary pricing reform

The pricing of electricity must above all **reflect its costs,** in other words, it must integrate all of the services rendered by the electrical system to its stakeholders (producers, consumers, systems operators, etc.).

The tendency to try to identify "good" solutions by manipulating the transmission tariff lever should not be taken lightly, and should be done in close collaboration with all stakeholders in the system. Thus, we might assume that an increasingly flexible electrical system will necessarily lead to a reform of the transmission price, i.e. the price of electricity will need to take into account the value of this flexibility and remunerate the service that it brings to the system. In the near future, with the development of digital technologies, real-time electricity pricing is a real possibility. Similarly, although local-scale innovation, like self-consumption, does not constitute flexibility as such, it will need to be taken into account in the pricing. The transmission price (TURPE)

43- The multi-annual energy plan represents the first step towards resolving this issue.

should in theory be increased for self-consumers that benefit from guaranteed access to the network in the case of a fault in their installation, but that only participate in the financing of the grid when they withdraw electricity[44]. Otherwise, the risk is that a vicious circle will set in, since the system will need to face a rise in the number of self-consuming customers who will mainly only pay for electricity based on the quantity of energy withdrawn – in other words very little – and a consequential repercussion of the costs of the grid on the other customers, who will pay most of the fixed costs. Self-consumption thus increases uncertainty for systems operators and requires additional flexibility margins.

The level and current structure of the TURPE, essentially based on an **energy-power ratio of about 80/20**[45], are also questionable components in electricity pricing, since the cost of access to the grid is above all dependent on the contract power and not the energy withdrawn. While the structure of the future TURPE 6 appears to confirm an increased power share, it is worth noting that this rebalancing of the energy-power ratio will not necessarily benefit some uses: for electricity-intensive uses, prioritizing power over energy in the tariff, all things being equal elsewhere, risks hampering the signals that increase energy efficiency, and reducing the interest of effective solutions[46]. **The energy-power ratio in the tariff should therefore depend on the type of usage and the price elasticity of the power required by such usage.** For a large share of domestic usages (secondary homes, disadvantaged households, etc.), the power required is not very sensitive to the price of electricity and justifies an increase of the power share in the price. This is less true for electricity-intensive industrial companies. Although a key feature of the transmission price is its uniqueness on the national territory (the "postage stamp" principle), it will probably be necessary in the long term to take into account the negative externality connected to the fact that variable RE is generally produced in areas conducive to its development (favourable weather conditions), and not necessarily in areas where mass consumption is located. This means transmitting the energy produced over long distances, and therefore requires reinforcing the electrical network that transports it.

3.4 CAPACITIES OPENED UP BY DIGITAL TECHNOLOGY

Intelligent control distribution

The wide-scale deployment of decentralized production calls for the parallel development of information systems, data exchange and control, in order to effectively mobilize flexibility systems. Digital technologies make a considerable contribution, enabling some forms of production (e.g. hydropower) to be operated much more precisely and closer to real time than has been possible up to now. Similarly, the dispatching of variable RE will require information exchanges at much more pertinent time scales between the different production sites.

The opening up of European markets to competition two decades ago has led to massive privatization, both for production and energy service provision. The digital transition that followed on its heels has led to technological innovations that boost flexibility: much faster capturing and reporting of data, smart grids, smart meters, more effective control-command apparatus, etc.[47]

Cybersecurity

The new energy landscape will include production and storage technologies, the decentralization of dispatch and control systems, and greater potential for their interaction. The penetration of digital technologies will facilitate this and lead to new usages, but will also increase the risk of vulnerability to cyberattacks. The phenomenon of hyper-digitization will raise considerable security challenges for managing critical infrastructures in a system whose continuous activity is indispensable. This therefore calls for stronger protocols to secure the communication of data essential to the operation of electrical infrastructures, in order to protect against the risk of failure caused by cybersecurity flaws and that could, in extreme cases, lead to a black-out. Following on from the various crises that have

44- And possibly injections in the case of partial self-consumption or injection into the network of all of the self-produced energy.
45- This ratio is much more favourable for power than for energy in other European countries where the transmission tariff essentially reflects the costs of accessing the grid due to very different grid use profiles and wide-ranging grid utilization costs. A noteworthy example is the Netherlands, where 100% of the transmission price is determined by a set of fixed costs (costs of connecting the customer to the grid) and capacity-related costs (costs linked to the availability of the grid in relation to the maximum power contracted by the customer). Source: European Commission Report on the tariff design for distribution systems in Europe (2015). https://ec.europa.eu/energy/sites/ener/files/documents/20150313%20Tariff%20report%20fina_revREF-E.PDF
46- An example is the use of a thermodynamic water heater, which is more efficient than its electric resistance equivalent.
47- It is worth a reminder that smart systems do not always only involve new technologies. A concrete example is the communications protocols used in managing the electric power system: the update of remote control musical frequency (TCFM), which dates back to the 1960s in the management of the French nuclear fleet and is used by Enedit to send peak/off-peak signals to households not yet equipped with Linky smart meters, has allowed some demonstrator projects to adjust the logical range of remote controls to respond to the system's flexibility requirements.

marked the last decade (housing, financial, economic, social[48], and most recently health), the possibility of a “digital crisis” triggered by the growing synergies between digital technologies and electrical infrastructures is not impossible, in particular given the exponential multiplication of energy data.

Risk of value control by foreign operators

Another impact of the digital transition is the increased European dependency on foreign equipment suppliers. The dominance of some players like GAFAM and BATHX[49], given the software infrastructures and applicative norms that they deploy all over the world and their understanding of artificial intelligence, accentuates the risk that these players will conquer Europe. This is even more likely in a world dominated by the data economy, and where personal data have become the hotbed of our information-centred society. The threat is therefore very real that these foreign operators could take control of value by taking advantage of the opening up of the European market to capture data, propose new innovative services, and become a kind of unavoidable interface between final consumers and long-standing operators. It underlines the need to consolidate France’s technological sovereignty and industrial competitiveness in terms of research on storage, flexibility technologies and low-carbon production, and innovations on networks and services.

48 - This refers to the “Yellow Vest” crisis that took place in France in 2018-2019 and its origin in the energy sector.
49 - GAFAM: Google, Amazon, Facebook, Apple, Microsoft for the United States; BATHX: Baidu, Alibaba, Tencent, Xiaomi, Huawei for China.

4 RESEARCH NEEDS AND PRIORITIES

The reflections pursued by the working group have identified a number of research priorities. This was done in concertation with the ANCRE alliance, whose vision is set out in **Annex 1.** At the same time, the group has attempted to briefly highlight the challenges and ideal conditions for carrying out this research. Many involve intellectual property and standardization issues that are key to establishing the future positions of French industry and to protecting the expertise of French companies.

Other priorities, relating to the operational functioning of the grid, need to be pursued in close cooperation with operators and subject to confidentiality. Those that concern national security should even be bound to secrecy.

Otherwise, and sometimes on different areas of the same subjects, it is on the contrary more advantageous to look outwards to benefit from studies undertaken in other countries and contribute to developing our international position. **The above analyses demonstrate that the electricity grid is a real system,** with technical, economic, social, environmental, international and political parameters whose variability and impacts increase with the growing number of actors and the opening up of European markets. This obviously has consequences on the way that research is carried out. In general, research needs to be more interdisciplinary and involve closer cooperation with public research, companies and public authorities.

4.1 DIGITALIZATION OF THE SYSTEM

Facilitating the penetration of digital tools in an increasingly decentralized electrical system will make it possible to mobilize new levers of flexibility (smart grids, load management, V2G, etc.) and new products and services that foster these flexibilities on European electricity markets, partly by using adequate communication protocols in system infrastructures in order to report back data faster. Digital technology will play a key role in the services that can be supplied to the network, which will necessarily be closely associated with setting up information and control systems: estimated balancing, voltage and frequency adjustment, prevention of a drop in inertia, etc. **Digital technologies provide system operators with a capacity to better anticipate flexibility control in real time,** bringing benefits like reduced congestion on the grid and the deployment of smart charging for electric vehicles.

Decentralization of management and dispatch

This involves employing sensors, software and interfaces using **data analysis and artificial intelligence** methods in order to better observe and control the grid. It also involves developing research on smarter digital distribution and on the interoperability of new components and their adaptation to the existing network.

Challenges include **intellectual property and industrial control of digital technologies,** along with control of markets, normalization, and national security (e.g. concerning exchanges of sensitive data between infrastructures).

Cybersecurity

Digital technological developments should also take into account **cybersecurity** and **cyber criminality.** This national security issue involves guaranteeing the protection of physical installations, communications between infrastructures, and the data that will be produced, processed and exchanged between all actors in the system, without forgetting digital solutions based on the use of algorithms (digital safes, blockchain, etc.).

Research priorities should concern the identification and management of risks related to: the vulnerability of an increasingly digitized electrical system; the resilience of this system (restoring operations in case of failure); and data protection and confidentiality. It would also be a good idea to identify technical solutions so that some stakeholders can play a role of trusted third parties.

Defence of value chains

This responds to the issues of **employment** and **technological sovereignty,** amplified by an unprecedented global recession. Defending value chains will be indispensable in an increasingly decentralized electrical system that will gather a growing number of stakeholders featuring major companies, start-ups and research laboratories. These stakeholders will have to maintain close connections with other energy systems, from production to the meter, and with other sectors (telecommunications, equipment manufacturers, digital solution firms, etc.).

Identifying areas sensitive to the development of these value chains will be crucial, along with cooperation possibilities, for example by setting up platforms for sharing knowledge and data.
Without doubt, the interactions between the design and achievement of these priorities, the interdisciplinary character of studies, and the need for cooperation between increasingly numerous and varied stakeholders, make it indispensable to implement a systemic flexibility approach that fosters the complementary use, or even hybridization, of different energy carriers and uses[50].

Annex 2 of this report sets out the main digital challenges in developing flexibility for the electric power system.

4.2
ADJUSTMENT OF ELECTRICITY PRODUCTION

In line with the updating of the nuclear fleet, and once the government has made a decision in 2022-2023 on a possible programme for new nuclear reactors, it will be important to ensure that these potential new reactors, like their predecessors, can adjust their production to correspond to daily and weekly fluctuations in demand. For wind and solar power, this will involve studying the injection and outage conditions, and developing the corresponding power electronics. However, the question of power electronics inevitably raises issues of intellectual property and industrial management.

4.3
REINFORCEMENT OF ELECTRICAL INTERCONNECTIONS

One of the goals of flexibility is in fact to minimize the need for reinforcement. However, high-voltage lines covering long distances will need to be created to benefit from the *scattered load balancing on transmission networks* provided by electric installations. The problem today is public acceptance of high-voltage power lines. Burying lines thanks to HVDC technology is expensive and will need to be compared with alternatives like storage, which is also costly.

4.4
SHORT- AND LONG-TERM STORAGE TECHNOLOGIES

Short-term storage, in line with battery programmes, will require focusing on two types of market:

- **Stationary batteries,** which will act as a buffer for variable RE and help maintain voltage-frequency quality.
- **Electric vehicles,** and their contribution to flexibility through a two-way grid connection (V2G).

50- Using gas or heat can for example bring additional flexibility to the electric power system.

Given the massive industrial investment in lithium-ion batteries, this sector should be the initial focus in order to counter Asian domination of the market. Research should be closely connected to improving processes. The challenges include bringing down costs further, improving performances (capacity, charging time, number of cycles, possibility of a second life, etc.), reducing carbon in manufacturing, and recycling materials.

The need to improve performances can justify a change of sector, which makes it important to maintain exploratory research on sectors other than lithium-ion.

For inter-seasonal storage, no economically viable solution at the 2035 horizon exists to date. However, the hydrogen programme and Power-to-X experiments can make a significant contribution to reducing carbon emissions and increasing the flexibility of the electric power system, provided that economic opportunities can be identified (business models). France has strong industrial assets and this is a domain where cooperation with Germany can be effective. For the future, mastering "decarbonated hydrogen" at the lowest possible cost is a key challenge. This is the object of the hydrogen programme presented by the French government on 8 September 2020 with a budget of €7 billion, almost concomitantly and in coordination with German initiatives (€7 billion) and EU schemes[51]. The economic viability of long-term storage technologies will require a multi-service approach.

4.5

DEMAND RESPONSE MANAGEMENT

Research priorities should concern injection and outage conditions, protections to be put in place against short circuits, and management of the associated power electronics. Here once again, intellectual property and industrial management will need to be considered.

4.6

DEVELOPMENT AND OPERATION OF MORE FLEXIBLE, EQUALLY RELIABLE NETWORKS

The challenge is to maintain voltage and frequency quality by adjusting the power at withdrawal and injection (from the very short to long terms), grid support, and grid forming. This will only be feasible after solving certain issues:

- **Technical issues:** systemic integration of mature information and communication solutions; mixed AC/DC architectures justified by the significant development of continuous current solutions (PV, electric vehicles, storage); deployment of improved synchronous compensators; creation of grid forming, e.g. using synchronous machines or virtual oscillators; design of rapid systems like restraining the RE energy yield to maintain frequency; multi-service storage at different time scales.
- **Economic issues:** definition of new business models to think in terms of total cost (CAPEX + OPEX); set-up of experiments (local energy cooperatives, V2G, storage).
- **Regulatory issues:** establishment of a framework for the concrete development of solutions at different levels, from living labs to industrialization; updating of norms and development of new ones; operating rules for local flexibility platforms allowing interaction between all stakeholders; reflection on access to and use of data at European level.

4.7

ECONOMIC MODELLING AT DIFFERENT SPATIAL AND TEMPORAL SCALES

Flexibility involves a transfer of risk: the security guaranteed by materials with a rigid response are replaced by much more supple, generally more effective management. The major challenge is controlling this risk, in other words the different contributors are responsible for the reliability of flexibility solutions. To ensure that techno-economic modelling can give a value to

51 - Sources: https://www.economie.gouv.fr/presentation-strategie-nationale-developpement-hydrogene-decarbone-france; https://www.lesechos.fr/industrie-services/energie-environnement/lhydrogene-le-pari-a-9-milliards-de-lallemagne-1210019; https://ec.europa.eu/commission/presscorner/detail/fr/ip_20_1259: for the EU, the Commission programme mentions IRENA's 2020 evaluations, which estimate cumulated investments in renewable hydrogen in the range of € 180 to 470 billion by 2050 and € 3 to 18 billion for low-carbon hydrogen of fossil origin.

flexibility, it is necessary to define what services flexibility provides to the electric power system, with inevitable uncertainties. It is crucial that the scenarios take into account these uncertainties (uncertainty of production and regarding consumption) at all spatial and temporal scales.
The requirements will therefore centre on:

- The development of **predictive models of RE variability**
- The capacity to **model flexibilities and include them in long-term investment** plans, along with modelling of future market architectures and/or energy price regulation when these prices do not currently give the right signals.
- The **quantification of the risk associated with taking decisions,** in particular since the line is becoming blurred between the different spatial scales (from the transport network to the user) and the different energy values (electricity, heat, gas). When moving down to the user level, the techno-economic approach will need to be combined with a behavioural modelling integrating social and human sciences.

This research will need to be carried out with an operational approach, in close liaison with companies and public authorities, and also with an academic approach, in order to participate in international exchanges on problems and solutions, in particular relating to the decarbonization of energy systems.

4.8 MARKET MECHANISMS

The aim here is to reduce the negative externalities resulting from the imperfections of current markets and historic electricity pricing methods (level and structure). This needs to be achieved in the context of an energy mix that is dependent on the degree of openness of the European market, increased competition between suppliers, the emergence of self-consumers, and the more or less redistributive effects of electricity tariffs: how can we maintain a basis of social cohesion and redistribution, like in the current equalized tariff system, while translating the real investment and operating costs?

This will involve identifying areas sensitive to the development of these value chains, and the potential for cooperation, for example by setting up platforms for sharing knowledge and data.

Without doubt, the interactions between the design and achievement of these priorities, the interdisciplinary character of studies, and the need for cooperation between increasingly numerous and varied stakeholders, make it indispensable to implement a systemic flexibility approach that fosters the complementary use, or even hybridization, of different energy carriers and uses[52].

52- Using gas or heat can for example bring additional flexibility to the electric power system.

5 EXPECTATIONS REGARDING PUBLIC AUTHORITIES, PUBLIC RESEARCH AND COMPANIES

5.1 REGARDING PUBLIC AUTHORITIES

In the very near future (by 2023, deadline of the next PPE), public authorities will need to make a number of decisions that will condition the future of flexibility in the French electric power system, and the resulting research programmes. These choices concern:

- **The electricity mix of French production,** considering the natural resources available, the security of their exploitation, their economic profitability, and naturally their likelihood to contribute to decarbonizing the system. Decisions will be crucial relating to the share of intermittent RE and nuclear power in the mix (taking into account the renovation of the current fleet by possible new generations of nuclear power stations). They will need to be backed by decisions taken at European level on the technical role of interconnections to provide flexibility in a system integrating increasingly high levels of unpredictable, incidental energy.

- **The reinforcement of "long-term indicators",** to send out signals to energy markets and thus stimulate interest in flexibility investments. This is particularly important in an economic situation where markets risk contracting in the very short term and where the economic recovery plan will play a crucial role.

- **The reinforcement of standards and access rules** to make flexibility assets of value more visible and profitable, with among other things an adaptation of market architectures and/or grid codes, which it would be a good idea to discuss extensively at European level. France should thus be able to position itself in European and international standardization bodies.

- **National coordination of investments** that will in the long term enable the programming of an increasing integration of RE by 2035 and beyond, new usages on the grid (e.g. V1G, V2G, V2H), along with different services provided to the system by different types of flexibility (voltage and frequency control, supply-demand management, etc.) based on the appropriate spatial and temporal scales.

- The reinforcement of public action on **energy saving and efficiency** for all sectors of the economy.

5.2 REGARDING PUBLIC RESEARCH

French public research on industrial matters has a solid reputation, both in terms of electricity production and management of transmission facilities. However, in an uncertain, threatening economic context including the arrival of new Asian actors armed with the latest technology, French research requires **stronger transdisciplinary connections between engineering sciences, economic sciences and social and human sciences.** Economics and modelling research can be applied to anticipate and monitor the activity of the electric power system at all levels, to size investments in flexibility, shed light on the operations of the market and public authorities, and identify more profitable business models for industrialists in the long term.

The reflections of the working group have identified the need for **greater, threefold coordination between, public research, private stakeholders and public authorities.** This coordination should work to showcase the French position and knowhow on energy research during European discussions. Participation in **European research programmes** like Horizon Europe and partnerships (co-programmed, co-funded or institutionalized)[53] should strengthen the scientific and technological bases of member countries and contribute to the smooth operation of the European electric grid, which has solidarity at its core and extends beyond the scope of political Europe. All of this should be done while making concrete the strategic political priorities of the European Union in terms of supply security, decarbonization, and renewable energies.

5.3 REGARDING COMPANIES

Technological innovation, new market rules, and changing regulations intensify European and international competition and trigger the emergence of new professions and players upstream and downstream in the value chain. **Cooperation between French stakeholders** is indispensable to boost France's industrial competitiveness and lead to an alignment between:

- **Technologies** that will be designed and experimented in the form of demonstrators, then matured on new equipment, means of production, storage and system management.

- **Industrial production processes** to face up to a potentially more restricting peak demand that will require setting up more flexible procedures in terms of their design and operation.

- The development of **innovative economic models** based on developments in the electric power system (green offers, demand-response offers, more appropriate pricing) that are profitable in the long term.

53- Partnerships in the Horizon Europe programme are divided into three groups: (i) co-programmed partnerships are based on agreement protocols or contractual agreements and define the commitments of all parties and the partnership objectives; (ii) co-financed partnerships are based on financial contribution to a programme in the form of a financial commitment by the partners; and (iii) institutionalized partnerships involve the participation and financial contribution of Member States and are implemented when the other types of partnership are not suitable.

ANNEX 1
THE ANCRE VISION OF THE ISSUE OF SYSTEMIC FLEXIBILITY

The current energy system results from a number of past technical and economic decisions made in a context far removed from today's ecological and citizenship motivations (i.e. the ambition for more local, controlled consumption). It would be extremely expensive to change the entire system, which needs to become more flexible, in other words capable of adapting and of overcoming the various challenges at every level of the spatial and temporal scale.

- **Long-term horizon (over ten years):** Integration of renewable productions and new usages (like electric vehicles and local energy communities); development of low-carbon hydrogen production to reduce emissions from industrial sectors and transport, in particular heavy vehicles; establishment of environmental indicators (extending beyond the carbon impact) taking into account the entire life cycle of technologies in decisions on investments and technology deployment.
- **Short-/mid-term horizon (from half day to five years):** Great variability in renewable energy production involving limited controllability and predictability.
- **Very-short horizon (less than one hour):** Drop in inertia on the grid due to an increase in power electronics associated with RE increasing the RoCoF (rate of change of frequency) and off-peak frequency.

To meet these challenges, the ANCRE GP[54] 10 on "Networks and Storage" has identified three key development areas: coupling of the different grids via Power to X; the evolution of methods and technological solutions employed for the development of grids; and greater involvement of usages and users in optimizing the overall system.

54 - Groupe programmatique – programme-focused group

1. Interactions between the different grids via P2X

One means of introducing flexibility is hydrogen, which is particularly interesting as an intermediate vector for interconnections of energy (electricity, gas, heat, fuel) by participating in cogeneration through fuel cells or Power to X, where X represents either electricity (Power to Power), synthetic methane (Power to Gas), synthetic fuel (Power to Fuel), or organic compounds (Power to Chemical). These technologies could also be used to store electricity on a large scale (inter-seasonal storage), helping to make the energy system more flexible.

- **Power to Power** involves converting excess electricity into hydrogen by electrolysis, then converting the hydrogen back into electricity via a fuel cell to satisfy a rise in demand, in return for a very mediocre energy chain yield. A first option is to use an electrolyser and a fuel cell operating at low temperature, like in the MYRTE project in Corsica. In this case, two separate systems (electrolyser and fuel cell) are necessary, thus increasing the amortization cost of the equipment. One potential solution to avoid needing two sets of equipment is high-temperature electrolysis that allows a reversible operation using a solid oxide fuel cell (SOFC), which is particularly interesting if waste heat is available on the installation site. The German company Sunfire has set up this kind of demonstrator on a Boeing site in California.
- **Power to Gas** involves either directly injecting hydrogen into the natural gas grid, or converting it into synthetic methane from CO2 using a methanation reactor, which is for example the case of the Jupiter 1000 project in Fos-sur-Mer, France.
- With **Power to Fuel and Power to Chemical,** chemical synthesis from hydrogen and

carbon dioxide is used to produce synthetic organic chemical compounds that can either be synthetic fuels, known as **“e-fuels”** like diesel or kerosene, or organic molecules with high added value.

The main techno-economic obstacle is that Power to X technologies are not yet mature and that infrastructures are expensive. This results in a crucial need for research and demonstration to validate the technical and economic interest of these solutions, and in particular inter-seasonal storage. In this context, ANCRE makes the following recommendations:

- **Develop high-performance technological resources with high TRLs** (electrolysers, synthetic methane reactors, high-power heat pumps).
- **Develop intelligent control strategies for the different grids** (gas, electricity and heat) to optimize technical and economic models around Power to X to estimate its long-term viability.
- **Make use of feedback from national and international projects.**

2. Sizing and operation of a flexible grid

The grid can be made more flexible by integrating a number of solutions, including:

- **Adjustment of power for withdrawals and injections** (from the very short term to the long term).
- **Grid support:** support for voltage and frequency regulation employing usages that behave like active and reactive power sources (from the very short term to the long term).
- **Grid-forming:** employing usages that behave like controllable voltage sources that do not require a voltage reference, thus allowing microgrid operation disconnected from the main grid (real time).

These solutions are at different stages of development due to technical, socio-economic and regulatory obstacles, with regulations being one of the main setbacks. The technical obstacles concern in particular: (1) **uncertainties** that increase with time but decrease as the spatial scale increases due to greater load balancing (RE production, electric vehicles, regulations, etc.); (2) **the variability of RE** sources, which limits their controllability and predictability without considerable technical and economic efforts; (3) **integration of flexibility models** (short-term horizon) in investment decisions (long-term horizon) and the **quantification of risk** associated with making decisions; (4) **the increasingly blurred line between the different spatial scales** (from transport to the user) and **energy scales** (electricity, heat and gas); (5) **the adaptation and interoperability of new components** in the existing grid; (6) the more complex **management of inertia.** These technological obstacles become more complex when the (direct or indirect) action of users is considered, requiring the integration of socio-economic models that can be difficult to couple with physical and mathematical models, like for example social acceptance. Lastly, norms and regulations are inadequate and/or unstable, which creates a significant gap between the maturity of a technological solution and its large-scale industrialization. Despite the existence of numerous demonstrator projects, their results and feedback are rarely used in subsequent demonstrators or to make progress in regulations. Therefore, the recommendations made by the working group can be ranked into five categories in decreasing order of priority and deployment potential:

- **Establishment of a regulatory framework** to enable the concrete development of solutions at different levels, from living labs and level-1 demonstrators up to replication on socio-economic fields. This framework should define clear rules for all stakeholders in the chain, and should be flexible and adjustable in line with feedback. It should in particular define the **different flexibility business models** in order to work on a TOTEX basis to estimate their economic impacts and the solutions required to make them competitive (local energy cooperatives, two-way V2G, storage, etc.). The report entitled “The smartEn Map PROSUMERS 2020” highlights regulations’ lack of adaptability in the development of flexibility at all levels of the grid in several European countries including France. The regulatory framework must also allow for the development of existing standards and/ or the establishment of **new standards** to reflect feedback and thus define a framework for future demonstrators. It should define operating rules for the **development of local flexibility platforms** that enable exchanges between stakeholders similar to what is available in other European countries. A last important aspect is a framework on **access and use of data** by the different stakeholders with a goal of overall optimization while protecting user privacy.

- **Development of digital tools** for modelling, simulation, optimization and information systems to be able to manage systemic optimization problems. In particular, **mixed probabilistic approaches** should be developed to deal with the high level of uncertainties. The growing volume of data available, partly thanks to the development of smart meters, requires developing **methods resulting from data analysis and artificial intelligence** to improve the observability and control of the network, and to refine standard hypotheses featuring in investment decisions. At the user scale, **behavioural modelling** should be combined with existing and future models. Lastly, **modelling of the environmental impact of technologies** must be integrated into decision-making in the form of an economic or performance indicator similar to average outage times for example.
- **Development of mature technological solutions via demonstrators:** Several solutions are already mature but require test and normalization phases before they can be deployed. For example: (1) **systemic integration** (architecting of mature solutions in terms of information systems, communication and information technologies and conversion, etc.); (2) **HVDC technologies** to control flows between different regions and support high-voltage networks with alternating currents; (3) **creation of artificial inertia** for example using synchronous machines or virtual oscillators (several demonstrators under way); (4) **multi-service storage** for which the investment costs can be recouped rapidly by providing services at different time scales and for different actors along the energy chain; (5) **rapid system services** like restricting RE production capacity to maintain a primary reserve to support the frequency; (6) two-way **vehicle-to-grid (V2G)** which faces challenges concerning conversion, compactness and the integration of new vehicles (in AC or even DC).
- **Development of solutions that break away from past methods:** grid **planning tools** must take on a multi-system, multi-scale, multi-energy vision that **integrates** the actions and **operational constraints** of flexibility solutions in a long-term vision. In addition, choices made in the past in a given context should not remain set in stone, which means investigating **mixed AC/DC architecture** solutions justified by the large development of DC usages (photovoltaic, electric vehicles and storage). The centralized vision of the grid must also evolve to become more decentralized, possibly leading to a **"clustering" of the grid** (smart microgrids or otherwise), in other words the grouping of usages that will be capable of providing grid-support or grid-forming-type services.

3. Flexibility through usage

Les différents rapports scientifiques démontrent As demonstrated by the various scientific reports, the potential exists in France for usage flexibility (i.e. at building or neighbourhood level), of almost 18 GW according to ADEME, which will be involved in providing services to the grid and managing user-related uncertainties to encourage users to consume energy at the point that it is available. All of this will take place in a context of complexity, uncertainty related to forecasting intermittent RE, *lack of load balancing* at very local scales, and more generally new equilibria in the energy system half way between centralization and decentralization.

One of the aims of usage flexibility is to move towards a smart-type approach, in other words, adapt production to consumption with innovative technologies, from a very local scale to a very global scale, to resolve problems like demand-side management, load matching and demand response, etc. and ultimately move closer to smart energy communities. This will make it possible to increase the rate of variable RE and transform consumers into prosumers for several energy carriers (electricity, gas and heat at building scale). Usage flexibility will also diminish constraints on the grid by limiting reinforcements, the consequences of which are very high investments for local authorities and negative externalities for inhabitants. The need to develop usage flexibility solutions is justified by: (1) **physical arguments:** buildings and vehicles perform increasingly efficiently (building consumption is more sensitive to user behaviour); (2) **practical reasons:** the spatial proximity between production and consumption at the scale of a single site (e.g. solar panels on a roof feeding a hot water tank in the house); (3) **ethical and legal questions** related to data, GDPR and protection of data belonging to consumers; (4) **political and democratic reasons:** involvement of local authorities and citizens, and the emergence of laws such as on self-consumption in France, or local (citizen and renewable) energy communities in Europe; (5) **the opportunity to create new values by managing RE locally** and in a context where short circuits are increasingly common; (6) **the issue of the adoption** and consumption of energy owned by the user and of the **involvement and acceptance** by individual citizens and communities in the investment process, management and governance.

The main obstacles identified can be divided into two types: (1) techno-economic obstacles related to **compensation for services provided to the grid by usage flexibility** in a context of increasingly complex and interconnected systems (greater need for resilience and cybersecurity in networks); (2) social obstacles related to **adoption and acceptance of technologies** by final users.

The research required to lead to the deployment of potential usage flexibility solutions concerns: (1) **uncertainty modelling at different time scales** of production, user demand, network flows and energy prices; (2) **financial models** concerning the investments and mechanisms that will generate prosumers taking into account current financial barriers; (3) **user behaviour,** to move for example towards digital twins of inhabitants to analyse their behaviour and test out solutions; (4) **dispatch management** to achieve optimization for both users and producers; (5) an **interdisciplinary-type approach** ranging from “system laboratories” in which prototypes are currently being set up, to living labs featuring individuals, organizations, companies and local authorities that aim to use and adopt these new technologies, and including field experiments, and thus creating an opportunity to study questions and tensions regarding issues of stakeholder involvement and acceptance; (6) digital: digitized networks and related cybersecurity, algorithmic digital solutions (from digital safes to blockchain) in order to manage problems related to GDPR, data privacy, and the necessary emergence of technical solutions and actors to ensure a role of trusted third-party, the emergence of open source, open hardware and open science and the transition towards an energy Internet; (7) **synergies with other networks:** telecommunication networks, Euro networks (actors and economic models ranging from investment to operation), legal and regulatory networks, and social networks (which will be coupled with energy communities and have a vocation to share energy).

Thus, the working group’s recommendations are as follows:

- **Develop R&D** in the field of i**ndividual self-consumption** (which has reached a good level of maturity, in particular in the tertiary sector), **collective self-consumption, and local energy communities** gathering major companies and start-ups to work on **multi-energy components** for production and storage at community scale.
- **Develop management and supervision software tools** compatible with GDPR directives: digital service platforms, development of the energy service industry, cybersecurity, etc.
- **Develop models related to usage flexibility:** economic, as well as social, territorial and citizen-centred, with a focus on indispensable regulatory developments. This all requires a space for deployment and innovation, in particular thanks to new EU directives on energy markets, which from a legal conceptual and regulatory point of view institute the concepts of Citizen

Energy Communities and Renewable Energy Communities[55].

- **Shift towards a "sociotechnical systems" approach,** based on social and human sciences (observation and understanding of perceptions and tensions) and the proposition of informed technological solutions aimed at managing complexity, involving all stakeholders (individual and collective, established players and newcomers).

55- Directive (EU) 2018/2001 of the European Parliament and Council dated 11 December 2018 on the promotion of the use of energy from renewable sources, establishing the concept of RECs (Renewable Energy Communities) https://eur-lex.europa.eu/legal-content/FR/TXT/PDF/?uri=CELEX:32018L2001&from=EN
Directive (EU) 2019/944 of the European Parliament and Council dated 5 June 2019, establishing the concept of CECs (Citizen Energy Communities).

ANNEXE 2
THE CHALLENGES OF DEPLOYING DIGITAL SOLUTIONS FOR FLEXIBILITY

1. Digital transition and the energy system: a sustainable revolution for all stakeholders

Arriving at the same time as the decentralization of means of production, and the democratization phenomenon55, the digital transition is one of the most impacting breakthroughs on the energy system. It comprises a set of tools and technical innovations: artificial intelligence, solutions for processing and storing data on a large scale (e.g. data centres), connected objects of all kinds, new-generation telecommunication networks, cloud or edge computing, blockchain, the smart economy, etc.

These new "totems" are part of a digital economy that has developed over more than two decades: from a vision at the start of the general public internet in the late 1990s that was highly centred on the computing sector, information systems and electronic commerce, to today's digital world increasingly orientated towards **new information technologies,** communication, and the social media economy. Digital technology has become a lever of change for operational processes for almost all industrial and tertiary businesses, and mainly employs data as its "fuel". Data that takes on a new meaning in the energy sector, because it is transformed into **information**, and then actual knowledge (e.g. customer profiles), in other words, into a **decision-aid tool** for both business leaders and public authorities. The aim is in particular to devise new economic models and offer products and services that are both innovative for customers and profitable for companies and the state. Digital solutions have thus led to the emergence of new skills and professions throughout the electrical system value chain: aggregators, flexibility operators, providers of energy as a service (EaaS) and platforms, new processes for systems operators (e.g. metering at more precise time scales, management of digitized infrastructures, intelligent control, command and dispatch, etc.). The reflections of the working group on flexibility have identified challenges related to digital technology that we group into technical, economic, social, environmental and regulatory themes.

2. Technical challenges

Digital technology is above all an i**ndispensable management and consumption lever,** both on a domestic level (e.g. hot water tank loads) and at the level of decentralized items like electric vehicle batteries. It is also central to the work of aggregators, through the tools that they employ: domestic boxes, sensors on objects, virtual power plants, etc. In addition, it will be one of the levers for designing more flexible electricity-intensive industrial sites (flexi-design).

At production level, an electric power system featuring more and more non-dispatchable energy will necessarily require boosting the role played by **supervision and control systems,** and the parallel development of information and exchange systems in order to effectively mobilize existing flexibility devices.

Digital solutions also play a key role in all services that can be provided to the network, which depend on the implementation of information and dispatch systems:

- **Anticipated balancing, frequency and voltage adjustment, prevention of drops in inertia** triggered by the greater penetration of variable RE, grid support, grid forming, etc.
- Capacity to **anticipate flexibility control in**

real time, or even on the day ahead, which assumes significant reliability of forecast data and therefore the possibility of obtaining data on a shorter time scale. Note that this real-time issue must also take into account the obstacle related to storing an exponential number of data: What technological means will be required? What will be the cost/benefit ratio for the system as a whole? What will be the limit of the environmental footprint of flexibility in terms of the energy challenge it addresses?

- **Decrease in congestion on the distribution networks; proposition by DSOs of alternative connection options** with occasional injection limitations depending on the constraints of works.
- **Deployment of smart charging apparatus for electric vehicles** by optimizing charging at times of day when it can limit simultaneous numerous power demands.

Lastly, the question of the development of **communication protocols** between connected infrastructures will be crucial, striking a balance between the need for technical progress on digital innovation and the associated risk management for system stakeholders.

3. Economic challenges

These mainly concern:

- **The electricity pricing model and the change in its structure (power/energy ratio)** that will need to better reflect the cost of accessing the grid, and could be facilitated by the functions featured on smart meters.
- **The impact of price signals** fostered by access to information technologies: need to relay scarcity signals[56] in real time and encourage investment in flexible resources.

4. Social challenges

A more flexible electric power system brings non-negligible social benefits insofar as it contributes to **reducing disparities in the world through secure supply, fewer tensions on installations, and more equal access to energy.** This takes place in a global context where energy needs have increased tenfold since the end of World War I, and where the population has tripled. In addition to the progressive reduction of technological costs, flexibility solutions are stimulated by the digitization of the system, which speeds up information exchanges. The digital transition therefore plays an indirect role in the reduction of energy disparities made possible by flexibility.

Another challenge involves acceptance by inhabitants: in some cases, flexibility can represent an alternative to new production means or new transmission infrastructures that can generate hostility from local residents. Clearly, easier control of existing equipment thanks to digital technology, both for production and consumption, has a positive impact on these questions of acceptability.

5. Regulatory challenges

These essentially concern the **guarantee of the security of physical infrastructures and data** exchanged in an increasingly digitized system, but also related ethical and legal questions: cybersecurity, data encryption, customer consent, protection of private life, confidentiality of information and communications, the third-party of trust role played by some stakeholders, etc.

6. Environmental challenges

The question of **dividing value between data and energy** is a real issue: the digital components and information technologies employed to manage these components appear to adopt an **increasingly energy-intensive consumption path as the rate of connectivity increases.** In the long term, this could point to an environmental footprint for digital usages that diverges widely from energy transition objectives:

- **Its share in greenhouse gas emissions could increase by 2030,** with some usages (e.g. blockchain) featuring very high growth, and research for less energy-intensive digital technology aiming at reducing it.
- The question also arises of **repairability**, component recycling, and final treatment of digital waste.

The deployment of flexibility should therefore involve reflections that consider more responsible digital solutions, both at the level of equipment production and related downstream usages.

GLOSSARY

AC/DC : Alternative current/direct current (courant alternatif/continu)
AC/DC: Alternative current/direct current
ANCRE : Alliance nationale de coordination de la recherche pour l'énergie (national alliance for energy research coordination)
ANRT : Association nationale de la recherche et de la technologie (national association for research and technology)
BATHX : Baidu, Alibaba, Tencent, Huawei, Xiamo
CAPEX : Capital expenditure
CCGT: Combined-cycle gas turbine plant
CEP : Clean energy package
DSO : Distribution system operator
EaaS : Energy-as-a-service
EMS : Energy management systems
GAFAM : Google, Amazon, Facebook, Apple, Microsoft
GP: Groupe programmatique (ANCRE's programme-focused group)
GW : Gigawatt = 109 watts (measurement unit of power)
HP : Heat pump
HVDC : High-voltage direct current
Hz : Hertz (measurement unit of electrical frequency)
IEA: International Energy Agency
Li-ion : Lithium-ion
OPEX : Operational expenditure
P2X : Power-to-X (electricity conversion pathway to another form of energy)
PPE : Programmation pluriannuelle de l'énergie (French multi-annual energy plan)
PV : (solar energy) Photovoltaic
RE : Renewable energy
RoCoF : Rate of change of frequency
RTE : Réseau de transport d'électricité (French electricity transmission system operator)
STEP : Station de transfert d'énergie par pompage (pumped energy transfer station)
TRL : Technology readiness level

NOTES

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