SCIENCE AND TECHNOLOGY BRIEFINGS
PARLIAMENTARY OFFICE FOR SCIENTIFIC AND TECHNOLOGICAL ASSESSMENT

Briefing 11

Electricity storage

February 2019

© Romain Chicheportiche

Summary

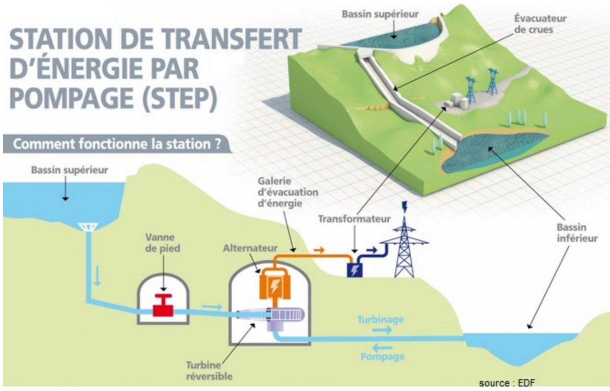
- *At the global level, electricity storage is likely to develop in a context of rapid growth in variable renewable energy (VRE) sources.*
- *However, simulations have shown that stationary storage needs will remain limited in the French context due to the flexibility of our electricity system and its interconnections with the European system. Significant storage requirements – especially inter-seasonal needs – are only likely to emerge after 2035, if an electricity mix consisting almost entirely of renewable means of production is established.*
- *Electricity storage is also a key issue in the rapid development of forms of sustainable mobility, at present for electric mobility, and in the longer term for mass hydrogen-powered mobility.*

Ms Angèle Préville, Senator

Different storage methods

Storing electricity means transforming electrical energy into another form of power and then converting this energy into electricity again, with losses inevitably occurring during each conversion.(1) Each storage method has particular characteristics that determine its practical fields of application.(2) This Briefing will mainly be discussing three methods:(3) pumped storage hydropower plants (PSHPs), batteries and hydrogen.

PSHPs(4) feature two reservoirs situated at different elevations with a hydroelectric generating set positioned between them, which can operate as a motor-driven pump unit or a power-generating unit. The upper reservoir is supplied with water pumped from the lower reservoir when the price of electricity is low. When the demand for electricity increases and its price rises, PSHPs inject electricity into the grid by passing water from the upper reservoir through a turbine. Using a tried and tested technique that provides massive energy storage capacity, high levels of power and satisfactory energy efficiency,(5) PSHPs are the most widespread method of electricity storage used in France and worldwide.(6) They also enable the production of low-carbon electricity (when the storage phase has been powered by low-carbon energy, as is the case in France). Therefore, potential resources need to be identified throughout the country(7) and environmental and economic offsetting measures should be devised to improve the population's acceptance of these projects. Lastly, it is essential to ensure that the rules used for setting electricity prices do not penalise storage facilities in general and PSHPs in particular.(8)



Batteries are a fast-developing storage method that converts electrical energy into chemical energy and vice versa. There are several different families of batteries which are categorised according to the pairs of substances used to create the electrochemical oxidation-reduction reactions, from traditional lead storage batteries to sodium-sulphur (Na-S), lithium-sulphur (Li-S) or nickel-cadmium (Ni-Cd) batteries, not forgetting the whole range of lithium-ion(9) batteries, of course, which sparked a technological breakthrough in the 1990s with their potential to be used in applications ranging from stationary storage and powering electronic devices to electric mobility. The performance of these batteries is improving in terms of their energy density,(10) excellent energy efficiency (90-95%), diminishing production costs(11) and satisfactory level of safety.(12) Without making the other electrochemical pairings obsolete(13), they are currently driving the rapid growth of the battery market.[14] Research priorities simultaneously concern safety, increasing energy density and cyclability,[15] and reducing the consumption of critical metals.[16] "All-solid-state" batteries[17] are expected to arrive on the market in 2022/2023, setting new standards for safety and density.[18]

Hydrogen is the third strategic electricity storage vector. "Power-to-gas" technologies enable the production of hydrogen by the electrolysis of water, which can be used to power fuel cells (FCs),[19] replace the hydrogen derived from the steam reforming of methane[20] in certain industrial processes, or be injected directly into gas networks.[21] It can also be used to produce methane by methanation,[22] which enables renewable gas to be used instead of natural gas of fossil origin. Lastly, this methane can be used to produce electricity in gas-to-power stations, with applications in the field of inter-seasonal electricity storage. Further progress needs to be made in electrolyser technologies[23] with the aim of significantly reducing the cost of electrolytic hydrogen.[24]

Electricity storage: a requirement to accomplish the energy transition?

France is actively engaged in the diversification of its electricity mix,[25] but the replacement of nuclear or thermal means of production, whose levels can be adjusted upward or downward, by wind and solar-powered resources that cannot be "controlled", implies **a much greater need for flexibility in the electricity system**.[26] This is the focus of reflections on the links between electricity storage and the management of the electricity system. Storage is one way to meet this need for flexibility in the system, because it enables a dissociation between the time of production and the time of consumption. For all that, claiming that storage is a prerequisite for the rapid development of variable renewable energy sources[27] would be an exaggeration, because it is just one of several ways to increase flexibility. Consumption management, the **geographical dispersion** of production sites afforded by electricity grids, and variations in the production of residual controllable means, can replace storage to a significant extent by adding sufficient flexibility to the electricity system. Beyond general considerations, defining the role of storage therefore implies a detailed analysis of the degree of interchangeability/complementarity between the different methods for increasing the flexibility of a given electricity system.

To understand the stationary storage needs in France,[28] it should first be stressed that the **French electricity system is already very flexible**. In addition to a large proportion of controllable means,[29] its flexibility is based on:

- a high-quality electricity transmission and distribution system, which is interconnected at the European level. Connecting all the continental production and consumption areas,[30] this offers **enormous opportunities for the geographical dispersion of production,** which have already enabled the residual European demand to be reduced to 75 GW annually.[31] For France alone, it has reduced peak production from 120 to 100 GW;[32]

- **management of consumption** by peak load shedding or staggering the times of consumption. The installed demand response capacity in France, which is lower than in the 1990s, corresponds to around 2.5 GW.[33] In addition, 11 million domestic hot water storage tanks, with a capacity of 9 GW, enable the staggering of almost 20 GWh of consumption to off-peak consumption periods. This tried-and-tested smoothing system is simple, inexpensive and efficient. By incorporating a more dynamic management system,[34] it could play a major role in the optimisation of renewable peak production periods;[35]

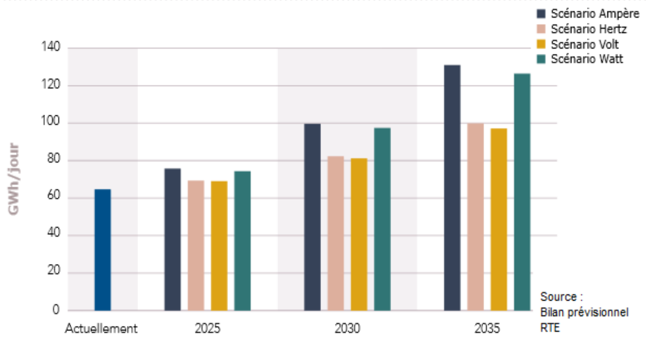
- lastly, **hydro storage**, which provides flexible solutions for all time horizons (including inter-seasonal, via storage reservoirs). At present, however, other storage techniques, including batteries, make only a marginal contribution to the flexibility mix.

Scenarios to quantify future storage needs

RTE (French electricity transmission network operator) and ADEME (French Environment and Energy Management Agency) are involved in activities to define the adaptations that need to be made to this flexibility mix in a context of energy transition. These forward simulations take account of numerous technical and economic parameters that remain uncertain at this stage, especially with regard to the future level of electricity consumption,[36] the extent of the diversification of the production mix,[37] the price of carbon, future developments and the decline in the cost of storage (especially with regard to batteries and the power-to-gas-to-power sector). Due to the large number of unknown factors, these studies define multiple development scenarios, which are themselves adapted into numerous variants. This culminates in the mapping of probable futures and can be used to formulate robust forecasts of the storage and flexibility needs.

In 2017, RTE produced four scenarios for the period to 2035.[38] These simulations[39] confirm that flexibility needs will increase significantly in all scenarios, but without leading to a significant increase in storage needs. In this way, according to the **Ampère scenario**, which is nevertheless an ambitious scenario for renewable energy sources,[40] most flexibility needs could be satisfied by hydro resources, interconnections and, to a lesser extent, the mobilisation of load-shedding resources – with this last solution appearing to be a cheaper way to meet the needs in peak periods than batteries.[41] A commercial market for electricity storage in 2035 only emerges in the **Watt scenario**, which is a radical departure based on the rapid decommissioning of the nuclear fleet with renewables accounting for 70% of the production mix. The significant development of wind and solar energy could indeed lead to periods of abundant low-cost production, propitious to profitable storage activities.[42] In addition, maintaining the security of energy supplies would then require a substantial contribution from all means of flexibility, combined with the development of gas-fired power stations.[43] RTE, which does not propose a precise assessment of the storage needs in this scenario,[44] still stresses that storage would not constitute a revolution at this stage.[45]

Évolution des besoins de flexibilité – exemple du volume d'énergie « déplacée » par jour pour répondre aux besoins du système électrique



The majority of the experts consulted agree with this conclusion, which downplays the potential for the development of stationary storage in France over the next 15 years. The diversification of the French electricity mix will not require a change of scale or technological breakthroughs in the storage sector until the mid-2030s. Maintaining a reasonably significant share of controllable production resources throughout this time frame,[46] accompanied by a moderate increase in demand response and PSHP capacities, and combined with investments in the grid to make it more "agile"[47] and more robust, will be sufficient to balance out the supply and demand over all the time horizons.

ADEME has examined even more ambitious scenarios for the development of renewables up to the horizon of 2050/2060, at penetration rates of 80 to 100%[48]. An examination of all the technical and economic aspects of these scenarios confirms that significantly increasing the storage capacities only becomes essential to balancing out the electricity supply and demand at every hour of the year once these substantial proportions of renewables have been reached in the production mix. Short-term storage develops once the 80% renewable scenario is reached, while inter-seasonal storage needs using power-to-gas and gas-to-power technologies[49] start to appear at a 90-95% renewable mix.

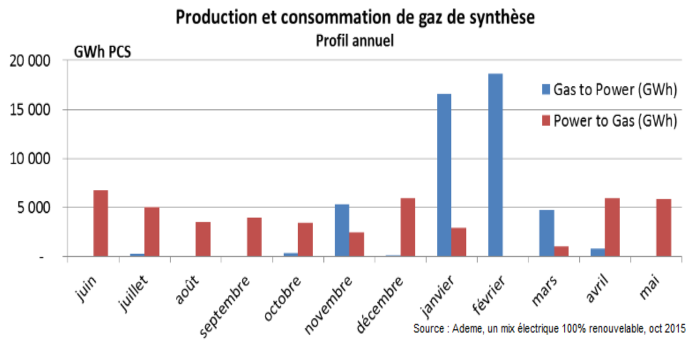
	Mix EnR			
Capacité installée (GW)	100 %	95 %	80 %	40 %
Stockage inter saisonnier	16,8	8,8	0,0	0,0
STEP	7,0	7,0	7,0	7,0
Stockage de court terme	12,2	10,9	8,0	2,2

Source : Ademe, Un mix électrique 100% renouvelable ?, oct. 2015

In these scenarios, the possibility of confirming the model therefore depends on the premise of the availability of certain technological breakthroughs.[50] The technical advances required are likely to concern two issues in particular:

- **addressing the loss of inertia in the electricity system**.[51] The rapid development of VRE sources, which bring into play a power electronics stage instead of direct connections to alternators, will lead to a loss of inertia that is currently provided by the rotating masses connected to the grid.[52] Today, in the event of a drop in the frequency of the electric current, the first correction comes from this spontaneous inertial response.[53] Therefore, the frequency variations for an identical initial imbalance are likely to be greater in the future.[54] Even if it were decided to reduce the nuclear fleet to such a significant extent, such high proportions of renewables would not be attained before 2035, which leaves sufficient time to develop the necessary techniques – particularly since solutions are already emerging: installation of synchronous compensators on the grid;[55] requirement for wind turbines to provide a rapid frequency adjustment service (referred to as "synthetic inertia"[56]); or radically rethinking the synchronisation and frequency control strategy, through "grid forming" activities.[57] In all cases, the use of batteries would then make a key contribution to the stability of the electricity system;

- **the development of storage resources adapted to the seasonal regulation of the electricity system**. In the case of very high renewable energy penetration rates, the arrival of winter requires the transfer of solar energy produced in summer for use during the cold season.[58] According to studies by ADEME, inter-seasonal storage needs are estimated at around 40 TWh. In order to reach maturity, this solution requires power-to-gas-to-power technologies, which are still at the demonstrator stage.[59] But once again, there is no urgency because the question of inter-seasonal storage will not arise before 2035.



Batteries and hydrogen at the heart of emerging forms of mobility

Improvements in the operating range of lithium-ion batteries and their declining production costs have prompted the automotive industry to embark on the **massive development of the electric car market**. Making this change is also an integral part of public policies to reduce greenhouse gas emissions.[60] However, this is posing several challenges for the public authorities, regarding:

- the conditions for the extraction of critical metals in the producing countries and their human and environmental impacts. It is essential to impose stringent CSR and traceability requirements upon battery manufacturers;[61]

- the securing of supplies of critical metals, particularly cobalt[62] and, to a lesser extent, lithium and nickel;

- the recovery and reuse of batteries throughout their life cycle (for use as a stationary storage solution when their performance becomes inadequate for mobility applications[63] and through the implementation of a recycling channel);[64]

- the position of French and European manufacturers in the battery sector, with the risk of a repeat of the catastrophic scenario seen in the photovoltaic sector. Today, the top ten manufacturers of Li-ion batteries are Asian.[65] The alliance between SAFT, Siemens, Manz and Solvay gives Europeans an opportunity to return to the market. It needs to be supported;[66]

- the establishment of an electrical recharging network capable of serving the entire country with non-proprietary terminals;

- the smart management of the impacts of mass electrical mobility on the operation of the electricity system in order to transform a potential constraint into a way to create flexibility.[67]

Hydrogen could also play a key role in future mobility applications. The carbon balance for hydrogen-powered mobility can indeed be excellent if low-carbon electricity is used for the electrolysis of water.[68] Although it is technically possible, the rapid development of hydrogen-powered mobility will continue to be held back by economic obstacles in the near future.

The first is the cost of electrolytic hydrogen. For hydrogen-powered mobility to be competitive in relation to electric or hybrid mobility, two conditions must be met:

- access to low-cost electricity for powering electrolysers for relatively long periods (around 4,000 hours per year). This requires a very high wind and solar photovoltaic energy penetration rate to enable long periods of abundant electricity production;[69]

- increasing the efficiency and service life of electrolysers. Progress similar to that seen for solar photovoltaic panels and batteries is conceivable but, without being improbable, remains at the conjectural stage.

Even if electrolytic hydrogen can be produced cheaply in the very near future, a second obstacle will need to be overcome: attracting the investments required for the roll-out and maintenance of hydrogen storage and distribution infrastructures. Is the creation of another energy network, in addition to the electricity grid, the gas network, heating systems and the future recharging network for electric vehicles, financially sustainable and economically justifiable? Although research must continue in preparation for the possible emergence of hydrogen-based mass mobility in the second half of this century, the emphasis in the shorter term should certainly be on encouraging more targeted hydrogen-powered mobility solutions and the mobility of heavy goods vehicles, local authority transport fleets or trains, as recommended by the Hydrogen Plan.

The OPECST's website:
http://www.assemblee-nationale.fr/commissions/opecst-index.asp
http://www.senat.fr/opecst/

References

[1] Electricity can be stored directly by using supercapacitors or exploiting the superconducting magnetic energy storage (SMES) principle. SMES involves passing an electrical current through a coil of wire transformed into a superconductor after being cooled to its critical temperature. If a short circuit is created in this coil, the current can then circulate around the loop thus created for an indefinite period, without any resistance and therefore without any energy dissipation due to the Joule effect. The stored energy is transferred to a load when the short circuit on the coil is opened. This enables the storage of energy in electromagnetic form. Combining high power density, very short reaction times and low energy density, these two direct storage methods have several useful applications but cannot meet mass stationary storage requirements or play a central role in the mobility sector.

[2] Storage methods can be categorised according to the energy vector used and characterised on the basis of parameters such as energy, power, response time, energy efficiency and service life.

[3] Electricity storage methods which are not examined in detail in this briefing include flywheels, redox flow batteries and compressed air energy storage (CAES). CAES uses compressed air as the energy vector, although the latest generations of the technology use the heat generated during compression. During a period of surplus electricity production, air is compressed at very high pressure (100 to 300 bar) for storage in tanks. The existing CAES schemes and the majority of those currently being developed use underground cavities (caverns and mines), but artificial underground or above-ground tanks can also be envisaged for lower-volume storage needs. The air is then released at times of peak electricity demand for injection into a gas combustion chamber and the generation of electricity by turbines. Although several "conventional" CAES systems are already in commercial operation, their economic performance is disappointing due to their low energy efficiency (approximately 50%), which falls short of the performance achieved by pumped storage plants and high-capacity batteries. Sites frequently mentioned include Huntorf in Germany (in service since 1979, generating 290 MW of power and providing 3 h of storage capacity), and McIntosh in the United States (opened in 1991, generating 110 MW of power and providing 26 h of storage). Research is focusing on the development of adiabatic or isothermal CAES systems enabling the recovery of the heat generated by the compression of air – which could increase the energy efficiency to 70%. Adiabatic CAES systems feature a thermal storage system that recovers heat from compressed air as it leaves the compressor. The heat is returned to the compressed air before it is fed into the gas turbine. Isothermal CAES systems are very similar but they recover heat during the compression phase. These techniques are still at the demonstration stage but could find their market in the intermediate-capacity stationary storage segment (ranging from 100 kW to 10 MW of generating capacity with a discharge time of around 4 hours. The strategic analysis carried out by IFPEN in 2014 to define its positioning in the storage sector highlighted the technological opportunities for redox flow batteries and CAES systems in this intermediate storage segment).

[4] Pumped storage hydropower plants. PSHPs belong to the family of hydro energy storage methods, which also include dammed lakes and weirs with locks. Hydro storage uses the potential mechanical energy of water as an energy vector. This energy can then be used to generate electricity on demand through turbines.

[5] The efficiency of a PSHP is between 70% and 85%.

[6] Exceeding 164 GW in capacity, hydro reservoirs and PSHPs account for nearly 97% of the stored electrical capacity worldwide (Source: data provided by the Équilibre des Énergies association, based on the Global Energy Database of the US Department of Energy, November 2016). PSHPs in France account for 5 GW in production (and 4.2 GW in pumping). There are six high-capacity plants in France: Grand'Maison in Isère (turbine capacity of 1,790 MW), Montézic in Aveyron (910 MW), Super-Bissorte in Savoie (730 MW), Revin in the Ardennes (720 MW), Le Cheylas in Isère (460 MW) and La Coche in Savoie (330 MW).

[7] In France, the Multiannual Energy Programme (Programmation pluriannuelle de l'énergie - PPE) of 27 October 2016 set the target of launching PSHP-type projects by 2023, with a view to developing 1 to 2 GW of capacity between 2025 and 2030. The new PPE for 2019-2023 / 2024-2028 confirms the need to develop this additional PSHP capacity. Additional hydro storage resources may also exist by raising the levels of existing dams, but detailed information about these potential resources is not available. When examining this issue from a long-term perspective, any estimate of the unexploited hydro potential should take account of the possible future impacts of global warming on the availability of water resources, in light of the fact that hydroelectric production is sensitive to climatic conditions. The average annual potential capacity is 67 TWh, but significant differences are observed between dry and wet years: e.g. 50.3 TWh in 2011 compared to 75.7 TWh in 2013.

[8] Certain stakeholders, such as the Syndicat des énergies renouvelables (the umbrella organisation for professionals in the French renewable energy sector), are calling for the public authorities to define a roadmap for remunerating resources that improve the flexibility of the electricity system, which would also take better account of PSHPs.

[9] Lithium-ion is a generic name covering a range of battery technologies which share the common property of being based on reversible flows of Li^+ ions between an anode (typically graphite) and cathodes generally made of a lithiated metal oxide in a non-aqueous electrolyte. Batteries are categorised as LCO (with a cathode made of $LiCoO_2$), NCA ($LiNiCoAlO_2$), LMO ($LiMn_2O_4$), NMC ($LiNiMnCoO_2$) and LFP ($LiFePO_4$). It should be noted that the LMP (Lithium-Metal-Polymer) technology developed by the Bolloré Group is not included in the group of lithium-ion technologies because it uses an anode made of lithium metal and a solid electrolyte.

[10] These performance levels have doubled over the past 20 years and will continue to improve. The current lithium-ion batteries provide energy densities of around 250 Wh/kg and 600 Wh/l. In comparison, the energy density of lead batteries is around 30 Wh/kg, with nickel-cadmium batteries at 50 Wh/kg.

[11] Costs have been driven down by technical progress made in the production of battery cells (which consume fewer expensive materials than in the past), and especially by economies of scale due to mass-production techniques. Prices have dropped from $1,000 per kWh in 2010 to $209 per kWh in 2017, and the price is expected to drop well below $100

per kWh before 2030 (source: figures provided for batteries by EDF based on a study by Bloomberg New Energy Finance).

[12] The use of lithium-ion batteries is not entirely risk-free. There has been a number of very high-profile incidents involving batteries installed in Boeing 787 aircraft, Tesla cars, mobile telephones and laptop computers (including Samsung's Galaxy Note 7). These incidents have been blamed on factors such as dendrite growth on the negative electrode which may create a short circuit in the battery and lead to runaway thermal reactions. The expected arrival of "all-solid-state" lithium batteries in 2022 should significantly improve safety.

[13] Lithium-sulphur batteries are the subject of particularly active research. These batteries provide high energy density (in theory 2,600 Wh/kg and in practice approximately 500 Wh/kg, i.e. twice the energy density of Li-ion batteries), but they deteriorate rapidly (several hundred cycles) as the sulphur cathode dissolves in the electrolyte. EDF is also working on the development of zinc-air batteries.

[14] The global battery market amounted to $63 billion in 2015, against just $25 billion in 2000. It could reach $115 billion by 2025 (source: written contribution by Équilibre des Énergies, citing a study by Avicenne Energy in 2017). It should be noted that this market is still currently dominated by lead storage batteries, but lithium-ion batteries will take over as the dominant segment in 2020. The battery market today is very largely driven by mobility needs, as batteries intended for stationary storage associated with the introduction of renewable energy sources (or "renewables") correspond to only 5% of the mobile market for the period up to 2023. Today, the lithium battery market for mobility applications corresponds to 120 GWh worldwide. It is predicted to rise to 500 GWh by 2025 (Source: Avicenne Energy 2018). Europe alone is expected to account for 20% of this global storage capacity.

[15] The cyclability of a battery characterises its service life. This is defined as the number of times (cycles) it can deliver the same level of energy after each new recharge.

[16] The CEA-LITEN Roadmap sets out the following goals for 2030: development of high-capacity, cobalt-free cathodes (> 1,000 Wh/kg), development of fast-charging (< 6 min) Li-S batteries (500-600 Wh/kg).

[17] The all-solid-state battery is based on the principle of replacing the organic liquid electrolyte with an inorganic solid compound enabling the circulation of lithium ions. Solid inorganic electrolytes are safer (they are non-flammable and prevent the formation of lithium dendrites). This type of battery also has a higher energy density.

[18] Target densities of 350 Wh/kg and 800 Wh/l are initially expected, followed by 400 Wh/kg and 1,200 Wh/l from 2025 onwards. In the longer term (beyond 2030), lithium-air batteries could become widely established, providing densities exceeding 1,500 Wh/kg.

[19] A fuel cell converts chemical energy from combustion into electrical energy, heat and water. The fuel supplied to the anode of a fuel cell is generally hydrogen, whereas the reduction reaction at the cathode is generally sustained by the injection of oxygen in gaseous form. There are several different families of fuel cells according to the electrolytes used. The most commonly used fuel cells are those of the Proton Exchange Membrane Fuel Cell (PEM) family, in which the electrolyte is a solid polymer membrane operating at low temperature.

[20] Methane reforming is the production technique for hydrogen, which does not occur naturally in its pure form (depending on the chemical reactions: $CH_4 + H_2O \rightarrow CO + 3H_2$ and then $CO + H_2O \rightarrow CO_2 + H_2$). This technique enables the production of H_2 at low cost but with a poor carbon balance (1 kg of H_2 produced by this process generates 10 kg of CO_2, according to the data provided by Équilibre des Énergies). 95% of global annual H_2 production (600 billion m^3) is obtained by steam reforming or other fossil-resource-based processes (catalytic cracking of hydrocarbons or coal gasification), and the rest by electrolysis of water. This hydrogen is mainly used in industry, for petroleum refining, ammonia production and manufacturing a variety of chemical products (methanol, amines, hydrogen peroxide, etc.), but it is also used in smaller volumes in the microelectronics, glass and agri-food industries for example. (Source: *Étienne Beeker, "Y a-t-il une place pour l'hydrogène dans la transition énergétique?" Analysis brief, France Stratégie, 2014*).

[21] Currently up to a proportion of 6% in France, limited by a regulatory constraint.

[22] According to the formula: $CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$. It should be noted that the CO_2 used for methanation could also be derived from methanation, with an environmental and economic complementarity existing between the two processes.

[23] There are three families of electrolysers, each currently at different stages of maturity: alkaline electrolysers (AEL), PEM membrane electrolysers (proton exchange membrane electrolysers - PEMEL), which are in commercial operation, and high-temperature electrolysers (- solid oxide electrolysers - SOEL), which are still in the development stage.

[24] CEA-LITEN is focusing on solid oxide electrolyser cell (SOEC - high-output, high-efficiency electrolysis) technology in particular, which offers significantly improved efficiency (+30% compared to alkaline electrolysers). The technological challenges concern the mass-production of the technology. In 2030, after the transition to the industrial phase which is predicted for 2026, the cost of producing hydrogen by the SOEC process is expected to be in the [€1.5 - €2/kg] range. The technology will then be technically mature enough for hydrogen-based applications in the chemical and transport industries. Thereafter, the ramping up of the hydrogen sector in both of these sectors could reduce the costs to point that it becomes competitive for the seasonal electricity storage applications that are expected to emerge in the 2035-2050 period due to the increase in the renewable energy penetration rate.

[25] According to French Law no. 2015-992 of 17 August 2015 on "energy transition for green growth", renewable energy sources must account for 40% of electricity production by 2030. According to the electricity report by RTE in 2017, production by hydro, wind, solar photovoltaic and bioenergy resources generated 96 TWh, corresponding to 18% of the electricity produced that year. Wind and solar photovoltaic power alone accounted for 6.3% of the total production.

[26] The flexibility of the electricity system means its ability to establish a balance between electricity production and generation despite the partially random variations that affect the levels of both supply and demand. The balance in question is between the power fed into the grid at any moment and the power withdrawn from it (instantaneous balance). It refers to the balance, over a given period, between the energy produced and the energy consumed. The flexibility

requirements for these different time frames (instantaneous, daily, weekly or seasonal) can be measured according to the notion of residual demand – which corresponds to electricity demand that still needs to be met after the production from variable sources has been taken into account. Before the arrival of VRE sources, the electricity system needed to be flexible enough to adapt to variations in demand according to very distinct daily, weekly and seasonal profiles. It also had to cope with two main uncertainties: firstly, the uncertainty concerning demand due to the vagaries of the weather (in France a drop of 1°C in winter temperatures in relation to the normal temperature leads to an additional power requirement of 2.4 GW, according to the data provided by Équilibre des Énergies); secondly, the uncertainty concerning supply, such as an accidental loss of production centres. The arrival of VRE sources has added a new electricity supply-related uncertainty related to the vagaries of the weather. As it is dependent on the strength of the wind and levels of sunshine, there is no reason for wind and solar photovoltaic-generated production to occur spontaneously at the level required to satisfy the demand. Consequently, it is observed that there is little correlation between the daily, weekly and seasonal production profiles of VRE sources and the electricity demand profiles for these same time frames. More precisely, solar photovoltaic energy generates an additional need for flexibility lasting several hours (intraday flexibility), whereas for wind energy, whose variation cycles usually last for several days after the geographical dispersion of production, tends to generate the need for several dozen hours of storage (daily or weekly flexibility).

[27] The expression "intermittent renewable energy sources" is frequently used. However, the expression "variable renewable energy" sources seems to be more appropriate, as it corresponds more closely to the idea of a continual and largely predictable variation between zero power and full power.

[28] The following details primarily concern the electrical system in metropolitan France, which is interconnected. The links between renewable energy sources and storage differ greatly in the non-interconnected zones of island territories, especially in French overseas territories where the opportunities for the geographical dispersion of production are, by definition, extremely limited. The low level of inertia in island electricity systems also leads to problems of stability once the proportion of VRE sources exceeds the threshold of around 30%. Finally, as the cost of conventional thermal production methods is extremely high in these regions, storage solutions – including the use of batteries – may be considered more economically attractive than elsewhere.

[29] Particularly for nuclear power, for which the load factor varies between 92% in winter to 64% in summer, which enables most of the inter-seasonal variations in consumption to be covered at the present time. The adjustments to nuclear power production are supplemented by the use of coal, oil or gas-fired power plants.

[30] Without the grid, the balance between the supply and the demand would have to be established throughout a smaller geographical area, which, during peak consumption periods would require the rationing of demand or the local use of production methods with high marginal cost. In the specific case of VRE sources, the grid also provides an outlet for electricity at peak production times that would otherwise be wasted. It is therefore a tool that can be used to foster energy solidarity between the areas of production and consumption, and also to moderate energy production. In addition, the grid also enables the pooling of system services that are essential to the stability of the electricity system and the quality of the electrical current supplied. The development of the grid plays a key role in all energy-mix-diversification scenarios.

[31] In relation to the hypothetical sum of the national residual demands in the event of European countries not being interconnected. This amounts to a 30% reduction in relative value.

[32] Source: written contribution by RTE to the Office's activities.

[33] Between now and 2035, the demand response capacity could vary between its current level and 6 GW depending on development scenario for the electricity system (RTE, Forecast Assessment of the electricity supply-demand balance in France, 2017).

[34] Domestic hot water storage tanks are currently controlled by a relatively basic off-peak/peak period-type pricing signal. If they were controlled by more sophisticated price scales or by new-generation consumption meters, it would enable a more precise smoothing of electricity consumption on a much larger scale.

[35] RTE's "Ampère" reference scenario points towards the emergence of a significant amount of production (9 TWh) for which there is no outlet. The conversion of this energy into heat for domestic use (domestic hot water) can therefore be envisaged. Source: RTE Forecast Assessment 2017, p. 205.

[36] The result of the simulations is quite sensitive to the hypotheses put forward for the future level of consumption. The flexibility needs vary according to whether it drops sharply or remains at a high level, with consequences concerning the level of CO_2, the storage needs, etc.

[37] One of the key questions concerns the extent to which the share of nuclear power and thermal power stations will be reduced and replaced by renewable energy sources, and the rate at which this will occur.

[38] Ampère, Hertz, Volt and Watt scenarios. Cf. Forecast Assessment of the electricity supply-demand balance in France, RTE, 2017.

[39] Over 50,000 simulations were performed for each hour of the year in this massive forward-planning exercise!

[40] In this scenario, renewable energy sources make up 50% of the energy mix in 2050 with a generating capacity of 149 GW and annual production of 314 TWh (against 294 TWh for nuclear).

[41] Cf. RTE Forward Assessment, pp. 201-205. However, this conclusion is directly related to the hypotheses adopted for the changes in the cost of batteries.

[42] Using stationary batteries to meet the electricity system's needs may then become profitable.

[43] In this scenario, RTE emphasises that under the current technological conditions, the scenario could not be implemented without installing new thermal facilities that would generate an increase in CO_2 emissions from the electricity system. Proportionally, the production of thermal origin should indeed double, rising to 20% of the electricity mix from its current level of 10%. For all that, the simulations performed do not confirm the claim that is sometimes made, which states that a system based on 70% renewables would require the "doubling" of the renewable capacity by thermal resources.

[44] When asked to propose a detailed breakdown of the storage needs, RTE declared that at this stage, further research is required to answer this question. "*This subject is being addressed by more detailed R&D activities: we have developed a methodology for systematically quantifying the flexibility needs of the electricity system according to different renewable energy penetration hypotheses. We are as yet unable to translate these flexibility needs into an optimal mix of flexibility solutions*" (response by RTE to the questionnaire transmitted in preparation for this briefing). To further examine the issue of determining the optimal combination of solutions, RTE launched the European OSMOSE (Optimal System-Mix Of flexibility Solutions for European electricity) project in 2018, for a period of 4 years. This project involves 33 partners and aims to find answers to the following questions: "What is the optimal flexibility mix?" and "What market rules are required to move towards this mix?" . A systemic approach has been adopted, covering the period to 2050.
[45] Forecast Assessment of the electricity supply-demand balance in France, RTE, p. 32.
[46] Even in the RTE's Watt scenario, controllable resources make up over 40% of the mix: 11% for nuclear and 18% for thermal, in addition to hydro resources which are mainly controllable resources.
[47] For further details, please refer to the RTE presentation package entitled: "Voyage au cœur du réseau de demain" (Voyage to the heart of tomorrow's grid) (March 2017). RTE is developing several solutions to optimise the performance of the transmission grid. In addition to testing "virtual transmission lines" in its Ringo project, RTE is also experimenting with new "smart" substations capable of handling up to 30% more electricity. In fact, the current substations often operate at above their maximum capacity because a sub-maximal amount of current is transmitted to prevent the lines from overheating. However, during periods of cold or windy weather, the lines are cooled and can accommodate more electricity than is permitted by the current safety standards. Therefore, the idea is to install temperature sensors on the lines in order to adjust the capacity of substations in real time without the risk of overheating. This is an example of future smart grids.
[48] Cf ADEME, "Un mix électrique 100 % renouvelable? Analyses et optimisations Un travail d'exploration des limites du développement des énergies renouvelables dans le mix électrique métropolitain à un horizon 2050", October 2015 ; ADEME, "Actualisation du scénario énergie-climat 2035-2050, October 2017; ADEME, "Trajectoire d'évolution du mix électrique 2020-2060", October 2018.
[49] The recent updates of ADEME's studies (Oct. 2017 and Oct. 2018) only marginally alter the 2015 estimates of storage needs.
[50] Which is not the case for the simulations performed by RTE.
[51] Inertia is the grid's ability to limit the frequency variations for 0 s to 10 s after a contingency event affecting the supply and demand. Inertia relates to the capacity of the rotors on rotating machines connected to the grid (thermal, nuclear and hydro power stations) to store energy.
[52] These rotating masses are primarily connected to the turbines on thermal, nuclear and hydro power stations. Solar panel installations do not incorporate rotating masses and although wind turbines feature significant rotating masses, they are not synchronously linked to the grid current frequency and therefore cannot be directly used to stabilise it.
[53] Due to the synchronous connection between their rotation speed and the frequency of the electrical current, any drop in frequency is counterbalanced by the inertia generated by the rotating masses.
[54] In its Watt scenario, RTE states that uncertainties relating to the stability of the electricity system appear at renewable energy penetration rates of above 70%.
[55] The technique consists in partially dismantling traditional power stations until only the alternator components remain (only the production turbine is actually dismantled).
[56] In this solution, VRE sources are required to provide access to a reserve energy source, which may be derived from the inertia of the wind turbine blades, or from storage devices (batteries, capacitors or inertia flywheels) in order to limit the frequency variations in the first moments of a supply-demand imbalance. However, there are two technical limitations to this solution which mean that it would only be appropriate for a limited renewable energy penetration rate. On the one hand, the synthetic inertia comes into play after a certain time lag in relation to the disturbance on the grid (a lag of approximately 100 ms after the loss of a power station or a sudden drop in consumption). When there is a high proportion of renewables in the mix, this reaction time is a major drawback, as the synthetic inertia can no longer ensure stability (the frequency variation is too great in the first moments due to the time lag). On the other hand, if the energy stored in wind turbine rotors is used to stabilise the frequency of the electrical current, their speed will diminish. If a wind turbine decelerates too much, the subsequent recovery phase may then be very long, and this will have a detrimental impact on frequency. Lastly, little is known about the impact of the ageing of installations on this type of process (source: written contribution by RTE to the Office's activities).
[57] This solution, which is still at the research stage, is the subject of the European MIGRATE and OSMOSE projects. The guiding concept is to designate certain solar photovoltaic power stations or wind farms (associated with batteries) as "lead facilities". Batteries could allow for rapid energy injections or the absorption of surplus energy to ensure stability during the first moments of the contingency event. In "grid-forming", renewables could therefore set the pace for the grid by modifying the frequency to coordinate the recourse to the primary reserves available at the level of the other production plants connected to the grid. This grid-forming strategy could address two major issues: grid stability (loss of inertia in the grid), and grid synchronisation in the absence of rotating machines to dictate the frequency of the grid. Furthermore, the grid-forming function would operate at any renewable energy penetration rate. However, this remains entirely at the theoretical level.
[58] As previously mentioned, inter-seasonal flexibility is currently ensured by ramping up the production of nuclear generating sets in winter, supplemented by thermal power stations. One potentially problematic issue for "100% renewable" scenarios (which is not absolutely certain at this stage), is the lack of economically and technologically mature inter-seasonal storage resources. Indeed, for daily and weekly flexibility, lithium batteries and PSHPs are technically and

economically pertinent solutions for meeting the consumers' capacity and energy needs, despite the unknown factors affecting the production of VRE sources.

[59] An example is the "Jupiter 1000" industrial power-to-gas demonstrator project, scheduled to start operating at Fos-sur-Mer in 2019. The plant is designed to be capable of transforming renewable electricity into gas for storage. The system consists of two electrolysers (alkaline and PEM), in addition to a methanation reactor and a structure designed to capture CO_2 from neighbouring stack effluent. It will enable the direct injection of hydrogen into the natural gas transmission grid at variable rates and will also allow for the injection of synthetic methane obtained from the recombination of renewable hydrogen and CO_2.

[60] Manufacturing a battery and enabling it to operate require substantial amounts of electrical energy, which means that its carbon balance will vary according to the electricity mix used for its production and recharging. However, at least at the European level, and even in countries with high-carbon electricity supplies such as Germany, the carbon balance for an electric car is still better than for combustion-engine-powered vehicles. In countries like France or Norway with very low-carbon electricity supplies, this balance is significantly better. Precise and detailed data can be found in the following publication: Dale Hall and Nic Lutsey, "*Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions*", The international Council of Clean Transportation, February 2018.

[61] Corporate societal responsibility.

[62] The production of certain critical materials is very highly concentrated at the geographical level (cf. Gilles Lepesant, La transition énergétique face au défi des métaux critiques, Studies by the IFRI, January 2018).

[63] However, as we have seen previously, the battery-powered stationary storage needs appear to be insufficient to offer a second life to all of the batteries that will be marketed for mobility applications over the next fifteen years. Stationary storage needs will only emerge if the penetration rate of VER sources reaches a very high level.

[64] This channel does not currently exist because the quantity of batteries to be recycled is insufficient for the development of an economically viable recycling channel. However, the expected massive development of electric mobility will create the conditions required for its emergence. It is nonetheless important to stress that this is not an urgent issue because the boom in the mobile battery market has only just begun and these batteries have an eight to ten-year service life in electric vehicles. This time needs to put to profitable use by investing in research in the most suitable recycling technologies and considering the appropriate regulatory adaptations.

[65] Seven of these 10 manufacturers are Chinese, including CATL which, with nearly a quarter of the global production, outstrips the Japanese manufacturer Panasonic. The two other non-Chinese manufacturers are South Korean.

[66] The French battery manufacturer SAFT is at the heart of an alliance with Siemens, Manz and Solvay aiming to develop two technological breakthroughs in the field of battery cells. The first will come into play in 2020 with the introduction of a new generation of cells incorporating active materials with low-cobalt content, and a graphite/silicon compound. The second will take place in around 2025 with the arrival of "all-solid" batteries. Investment decisions will need to be made very quickly to enable this technology to be installed in the new electric vehicles that manufacturers are planning to launch in 2022. This explains the need to support this alliance between SAFT, Siemens, Manz and Solvay. Supporting the European battery industry can also be legally justified on grounds of environmental criteria. As battery production is a highly energy-intensive industry, it generates more CO_2 emissions in Asia than in Europe (and more in Europe than in France), as the Asian electricity mix contains much higher levels of carbon. The CO_2 balance for the electrification of mobility is therefore much better with European batteries.

[67] The recharging periods must be managed to prevent excessive power demands from destabilising the grid (which can be done with adapted pricing schemes). Using the batteries of electric vehicles as a resource to increase the flexibility of the system can also be envisaged, with the charging needs being synchronised to peak or diminish according to the needs of the electricity system or the available resources (e.g. solar recharging), or even via the injection of energy from the batteries into the electricity grid to meet electricity consumption needs or to provide certain system services (Vehicle-To-Grid application).

[68] Rather than generating CO_2 emissions, the combustion of hydrogen in a fuel cell (FC) produces water. Hydrogen-powered mobility, in the strict sense, is therefore very environmentally friendly.

[69] It could be envisaged in electricity mixes with renewables exceeding 80%.

Experts consulted

- Mr Yves Bamberger, President of the Works Committee, and Ms Muriel Beauvais, Vice-President of the Works Committee (Académie des Technologies);

- Messrs Jean Bergougnoux, President, Étienne Beeker, Scientific Advisor, and Gilles Rogers-Boutbien, Secretary-General (Équilibre des Énergies);

- Messrs Yannick Jacquemart, Director of R&D and Innovation, and Philippe Pillevesse, Director of Institutional Relations (Réseau de transport de l'électricité – RTE);

- Mr Dominique Jamme, Deputy Director-General, Mses Pauline Henriot, Policy Officer, and Olivia Fritzinger, Institutional Relations Officer (Commission de régulation de l'énergie - CRE [French Electricity Regulation Commission]);

- Messrs Marc Jedliczka and Yves Marignac, Spokesmen (NégaWatt Association);

- Mr François Kalaydjian, Director of Economics and Monitoring, Mses Valérie Sauvant-Moynot, Head of the Electrochemistry and Materials Department, and Armelle Sanière, Head of Institutional Relations (IFP Énergies Nouvelles);

- Ms Florence Lambert, Director of the Laboratoire d'innovation pour les technologies des énergies nouvelles et les nanomatériaux (LITEN [Innovation laboratory specialising in new energy and nanomaterial technologies]), and Mr Jean-Pierre Vigouroux, Head of the Public Affairs Department (Commissariat à l'énergie atomique et aux énergies alternatives – CEA [French Atomic Energy and Renewable Energy Agency]);

- Ms Astrid Lambrecht, Head of Research at the CNRS (French National Centre for Scientific Research), Kastler Brossel Laboratory, Deputy Scientific Director of the Institute of Physics at the CNRS (INP/CNRS);

- Mr David Marchal, Deputy Director of Sustainable Production and Energy (ADEME);

- Mr Patrick de Metz, Director of Environmental and Governmental Affairs (SAFT);

- Mr Henri Safa, Research Physicist;

- Messrs Sean Vavasseur, Head of "Electrical Systems", Alexandre Roesch, General Delegate, Ms Marianne Chami, Member of the "Industry and Innovation" Commission and Head of the "Storage Solutions Programme" of CEA LITEN, and Mr Alexandre de Montesquiou, Ai2p consultancy (renewable energy syndicate);

- Mses Louise Vilain, Strategic Coordinator of the Electricity Storage Plan, and Véronique Loy, Deputy Director of Public Affairs (EDF - nationalised French nationwide electricity producer and distributor).