TerraWater

Energy scenario for carbon neutrality in France in 2050 and beyond

Ensuring that the promises made by France today are fulfilled in the future

Version 1.0

Voices of Nuclear

Contents

Robust, sovereign, sustainable, low carbon: a case study for future energy mix

A crucible for energy mix experiments, the European Union offers a chance for the rest of the world to observe and draw their own conclusions before adopting the measures necessary for the reform of their own energy systems. These measures will consume their financial and material resources, tax the credit they have with their voters, and take up the limited time we have left before running out of options. The lessons first learned by the European experiments hence had best be well understood and shared. We may not collectively be given that many chances at "trial and error".

More than 27 countries on the European continent, and as many different approaches to a country's energy mix. Each the result of its own specific resource availability, economic wealth, cultural heritage, neighbouring countries, geopolitical ties, and history. More than 27 countries bound together by overarching stakes such as climate, environmental protection, and energy sufficiency, as well as by physical electrical connections, imposing on all the Europe-wide consequences of their individual energy choices. When Poland struggles to phase out coal, its particulates and toxic gases have health effects on everyone; when Germany chooses to depend on Russian gas, the whole Union bends to Vladimir Putin's aggression; when Denmark chooses to cover the Baltic sea with batteries and windmills, the consequences on ecosystems impact the fish stock and marine biodiversity of the entire region; when France relies on nuclear power, the competitiveness of its industry rises sharply.

Among these countries, France has always drawn interest as one of the economic powerhouses of the EU (2nd in GDP and population), and as the proof-of-concept of a country having made the historical choice to rely heavily on electricity, and for up to 70% of it on nuclear. But France made this choice in the 1970s, in a context of events and challenges that have since been enriched by new ones: environmental protection, biodiversity loss and climate change.

Today, it must decide anew the direction it will give its future energy system, and the criteria on which to base its choice.

Voices of Nuclear, an NGO of volunteer energy enthusiasts and experts, has decided to participate in this effort and propose an approach that has been radically missing in the debate: a search for the pure technical optimum, free from dogma, interests, and presumptions, aiming for optimally achieved climate protection, minimisation of environmental footprint, solidarity at all levels and sovereignty of national energy supply, and using energy sources for what they do best, not for what we claim they're good at.

We believe the methodology applied and the conclusions of this search for the optimum French energy mix, may be of interest to France's neighbours and beyond, not only because of the impact France's choices will have on their own electrical system and economic welfare, but also because it can contribute to their own thought process on the topic.

The crucible is just getting richer and richer as European Member States struggle to make up their mind and decide on a course, in the face of urgency and of the growing impatience of their populations and industries. Let's hope they will manage to find a course as realistic and successful as TerraWater demonstrated it could be for France.

Foreword

This document presents the transition scenario proposed by the association Les Voix du Nucléaire[1] ("Voices of Nuclear") to ensure that France achieves a reliable long-term low-carbon energy mix by 2050 and beyond.

This scenario follows on from a vast study published in October 2021 by the French transmission system operator, Réseau de Transport d'Electricité[2]. Commissioned by the French government, it evaluates the potential scenarios for achieving by 2050 a national electricity mix that is compatible with the political ambition of carbon neutrality enshrined in the French National Low Carbon Strategy[3]. The study selected six different scenarios, ranging from a 100% renewable mix to a 50% nuclear mix.

Voices of Nuclear commend RTE's work and have elected to continue this prospective work.

Our scenario is motivated mainly by the need:

- to counter the climate and environmental perils that threaten a happy future for our children,
- to guarantee energy security for citizens.

The principles of this scenario are underpinned by the conclusions of IPCC climate reports, IPBES biodiversity reports, and UNDP Human Development Reports.

It aims to fuel prospective thinking about our energy future, and to foster the emergence of proposals concerning the quality of the energy delivered to citizens, the reduction of greenhouse gas emissions, and the protection of natural areas and biodiversity.

The Voices scenario makes no claim to mirror the depth of the remarkable work carried out by RTE. However, it does intend to remain independent of the constraints inherent to the consulting process adopted by the operator with regard to the various industrial sectors involved.

We have updated and re-evaluated the potential of each sector, without considering the political and market context that was applicable to each one and embodied in their declarations. This has enabled us to propose a strictly technical and industrial interpretation of the capacities to be deployed.

Voices of Nuclear have thus ensured that they are free to explore all avenues, with a successful energy transition as their sole obligation.

Developments and clarifications

This energy scenario encompasses all the components required to ensure an effective and coherent pathway to carbon neutrality and maintain it in the long term.

The Voices scenario will be regularly updated, thereby integrating detailed modelling of certain points (needs to upgrade the electrical system and the associated costs, costs of additional installed capacity, potential in terms of geothermal energy and nuclear heat co-generation). This will be done in particular in the form of appendices to the report on subjects such as PSPs, the back end section of the nuclear fuel cycle, or energy efficiency of buildings.

1 Hereafter referred to as: "The Voices" or "the association" or "we"

2 RTE

3 SNBC

Approach and stances

The aim of this energy scenario is to sideline fossil fuels as quickly as possible to achieve the objective of carbon neutrality, and to do so while minimising the uncertainties arising from the assumptions regarding technologies, costs and behaviours. Without denying that advances in technology, costs and behaviours are both possible and desirable, the Voices propose this scenario. Drawing on this basis, it will be possible to integrate other assumptions as these advances become a reality - and not before - in order to ensure that the promises made to future generations are kept.

Through this scenario we have sought to minimise complexity and impacts while optimising use of resources. Our aim was to eliminate the superfluous and minimise unnecessarily costly complexities (financially, socially and environmentally speaking) associated with the alternatives: little hydrogen, no gas network in the long term, few batteries, a resource-efficient approach to power lines and interconnections, minimal mobilisation of agricultural land for energy production, and as little as possible industrial development of natural land. This efficiency-based approach is applied not only to energy services provided, but also from the beginning to the guiding principles and the ways to meet them.

There are, therefore, three corollaries to this approach. First of all, the Voices scenario considers the increasing sobriety in end uses not as a core assumption but as providing a desirable margin, and therefore keeps sobriety outside its scope from a purely technical point of view. It also makes little use of demand-side management, which brings its own raft of uncertainties. Beyond a small number of simple actions, demand-side management on a large scale makes extensive use of digital technologies, which potentially require large quantities of critical metals and components[4]. This also requires behavioural changes that are too uncertain to be rigorously integrated into long-term forecasts. Lastly, this scenario chooses to rely on mature technologies, resulting in the focus being placed on relatively "low-tech" options: pumped-storage plants (PSPs[5]) and wood energy, rather than hydrogen and batteries, for instance.

In agreement with many experts in the field and EDF's declarations, the association considers that the commonly accepted limit of 14 new EPRs by 2050 is probably based as much on an absence of long-term visibility and political will and support as on a real lack of industrial potential. Indeed, capacities that previously existed can be restored if the necessary time and resources are allocated[6]. The association also notes that there is in principle no technical impediment to extending the operation of French reactors beyond the 60-year mark, provided that this extension is anticipated.

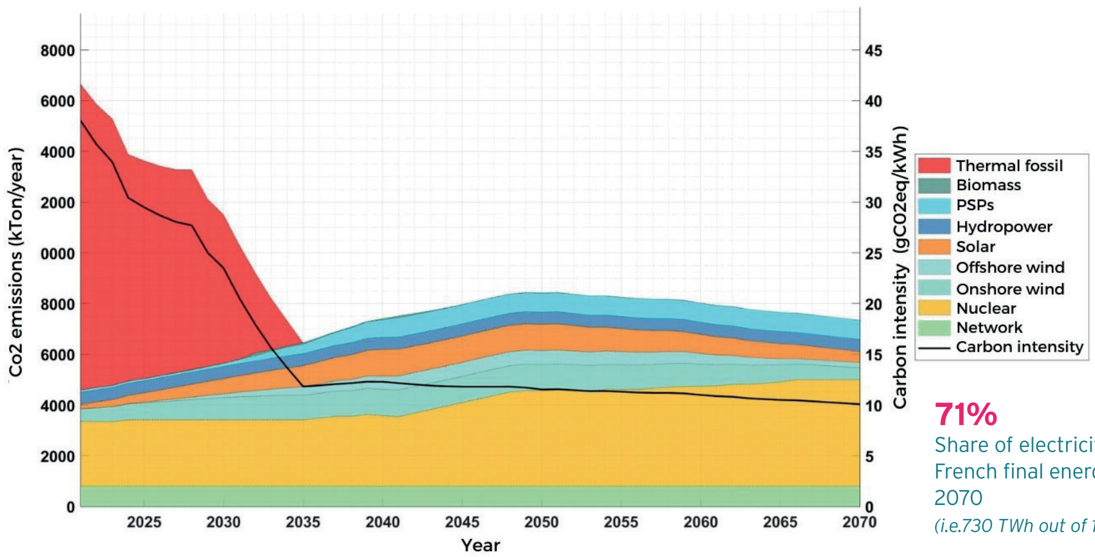
4 https://ec.europa.eu/growth/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en
This has two major advantages:
If only one element in a process does not yet exist commercially, there is minimal uncertainty about its capacity for deployment (as is the case with biomass turbines, the concept of which was validated 40 years ago).
"Low-tech" technologies are by their very essence more resilient: they make little use of mineral resources, particularly metals, and they reduce the environmental impacts related to the mining of such resources and the vulnerability to economic or geopolitical uncertainties inherent to procuring them (take, for example, the case of pumped-storage hydropower, which requires very few critical metals in comparison with other energy storage technologies).

5 Pumped-Storage Plant: a system based on two reversible dams that currently accounts for more than 95% of energy storage capacity worldwide.

6 Public consultation BP 2050 – Response from EDF: "As stated for the N2 scenario, France's industrial sector, in its current configuration, is indeed capable of absorbing an average development rate of one new EPR reactor per year, leading to 25 GW of new nuclear generation capacity in 2050"

Variations in the carbon footprint of electricity on the path towards electrifying and decarbonising the French energy system

24%
Share of electricity in France's final energy mix, in 2021 *(i.e. 440 TWh out of 1830 TWh, net)*



71%
Share of electricity in the French final energy mix, in 2070
(i.e.730 TWh out of 1030 TWh,

Carbon footprint of France's electricity mix, as it varies and as its share in the final energy mix increases. The increase in the amount of electricity produced in absolute terms stems from the effort to electrify uses, reindustrialise and enhance the self-sufficiency of France. Electricity thus represents 24% in 2021, and 71% in 2070, of an overall final energy mix that decreases in absolute terms.
> (calculated as a net value, factoring in network losses and the incorporation of international bunkers) and on the basis of the CO_2 emission benchmarks in force in 2022

To achieve carbon neutrality by 2050, this scenario relies on the massive and systematic electrification of almost all end uses where this is possible, focusing mainly on the electrification of the three pillars: industry, road transport and heating of buildings.

In the early 2020s, France consumes approximately 480 TWh/year of electricity, with a record peak consumption of 102 GW (reached on Wednesday 8 February 2012 at 7pm). The assumptions adopted imply that, to achieve carbon neutrality in 2050, and depending on the energy efficiency and conservation improvements made, electricity consumption would be around 750-800 TWh/year in the baseline scenario (well above the 650 TWh/year stated in the French National Low Carbon Strategy). Under such conditions we envision a maximum consumption peak of 155GW.

The decision to pursue electrification to such a high degree, compared to other energy scenarios that have recently emerged, is driven by a **desire to make minimal use of biomass** (whether solid, liquid or gaseous). The first reason for this relates to the climate and the environment in general: biomass is the energy source that requires the most land per unit of energy produced. Yet biodiversity is already under pressure due to the loss of greenfield land, the management of water resources and the major conflicts of use that will arise in the future over land areas that are accessible and exploitable. If one also considers the importance of wood as a renewable construction material and a carbon sink, it seems necessary to reserve biomass for uses in which it is absolutely essential. Given, moreover, that one third of the oil consumed is not used as fuel, the availability of an abundant source of carbon material such as biomass will be necessary for the petrochemical sector, a role which this material will then be able to take on if it is reserved for this purpose.

The second reason is economic: a large part of the biomass predicted by the French National Low Carbon Strategy consists of biogas. However, for stationary uses, biogas remains less competitive than direct electrification, and only a few strictly non-electricity uses with "high added value" justify its existence. The main use could be marine fuels for cargo ships, whose final energy consumption amounts to 21 TWh/year in France, followed by international air transport, accounting for 68 TWh/year.

The Voices scenario also attaches great importance to the country's sovereignty and independence in terms of its electricity supply. The electrical system modelled in the framework of this scenario must hence be capable of operating in the "self-sufficient France" configuration. This means that it must be able to guarantee its own supply capacity at all times, including periods of peak demand. By making this choice, it is not dependent on interconnections with neighbouring countries and hence on their energy choices.

This vision is in line with the historical choice France has made in designing its power-generating facilities, to which its citizens owe their confidence in their country's ability to meet their needs. However, it contrasts sharply with the European vision of resource pooling and interdependence that has been in place since 2011[7] and is strongly emphasised in the RTE scenarios. This pooling of generation - to the extent that interconnectors are depended upon for almost an hour a day on average[8], in normal operation - is generally justified by the assumption of reciprocity and short-term economic optimisation. But this assumption is fragile. There will never be a guarantee that this interdependence between countries will be balanced or that this balance will be respected. As we have seen again in recent times, states in crisis often place the priority on their own interests[9], even in situations where cooperation would provide more efficient management. Under these conditions, endorsing and reinforcing interdependence between countries that are not and will never be equal in terms of sensitivity to imports, with diverging political and economic interests, when dealing with an energy vector as instantaneous as electricity, is a risk that Voices of Nuclear consider significant. It is a matter not of calling European solidarity into question, but of strengthening it by restoring and gradually increasing the margins available to assist countries facing a shortfall. Moreover, the simulations performed by RTE show that the additional cost of ensuring that the country has full capacity to meet demand under all circumstances does not exceed 5% of the total cost of the system.

The Voices scenario involves massive electrification of all end uses to ensure it is technically, economically and socially realistic. It **chooses not use gas - including non-fossil gas, based on biomass or hydrogen - to generate electricity**, in order to avoid major technical and environmental constraints. In doing so, it bypasses the risks that gas use entails, and the need to maintain, in parallel, a large gas network that is less versatile than the electrical system.

Other major technologies, such as geothermal energy and nuclear cogeneration, will also have a key part to play and this will be evaluated in future versions of this scenario. Without radically transforming the profile of the proposed pathway, these additional low-carbon production capacities will boost the margins, essential to safeguarding the ambitious objective of profoundly transforming our energy system in less than 30 years.

Technical revolutions may also take place one day - a solution for storing electricity other than with water, infinitely recyclable materials, nuclear fusion, and more... Ultimately, lifestyles will no doubt undergo further change - for the better. All these developments will have a rightful place in this scenario, and **the search for that place must continue.** But if they do not succeed, or not as quickly as hoped or predicted, the energy transition will take place nevertheless, and that development time will have been put to good use, because our societies will be functional and will have the time, intelligence, resources and energy to devote to them.

7 RTE, "Energy Futures 2050" study (in French), Chapter 7 "Guaranteeing supply security", p.286
"Since 2011, the supply security assessment defined in the French Energy Code has included the contribution of neighbouring countries in supply-demand balance modelling."
8 "Imports strictly necessary to guarantee supply security at least 3% of the time, i.e. more than 45 minutes per day on average."
9 As is the case with exports of wheat from some countries as a consequence of the invasion of Ukraine by Russia in 2022 or the measures taken by Norway in 2022 to curb electricity exports to the rest of Scandinavia.

The opportunities offered by a significant development of geothermal energy, nuclear cogeneration or advanced technologies, that have yet to materialise, as well as substantial changes in the consumption habits of individuals, companies or public establishments, could be harnessed to **ease the main point of tension identified: potential delays due to social acceptability issues, which could adversely affect the rate at which the scenario's components are deployed** (wind, solar, nuclear, PSPs, high-voltage transmission lines, etc.).

Variations in electricity generation by source

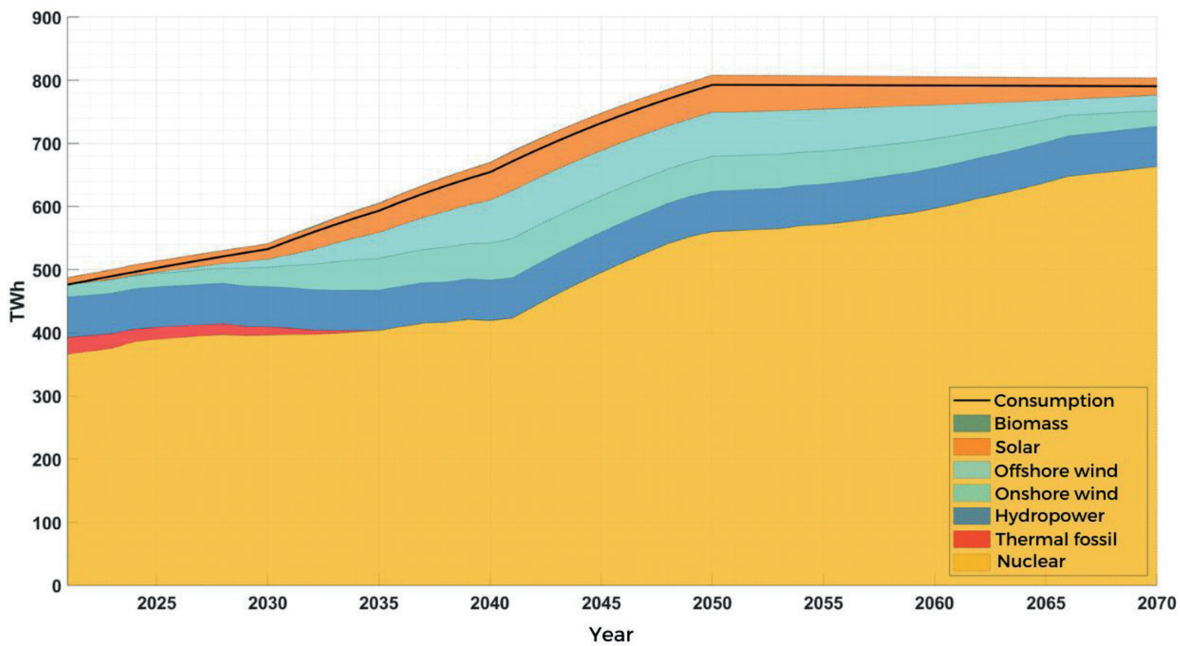


Fig.2 - Projection of the electricity generation mix of mainland France up to 2050 and beyond, fully low-carbon as of 2035, on the basis of the Voices scenario. N.B.: Combustion turbines generate a maximum of 1 TWh in 2041, and are hence invisible at this scale.

To conclude, the driving force of this scenario is to minimise the uncertainties arising from the maturity level of the sciences and techniques harnessed, the networks and sectors called upon, as well as uncertainties associated with a profound change in uses and habits. While the association encourages citizens to change how they consume resources and energy, we choose not to make the country's energy security dependent on a social transformation that remains uncertain and is still not widely accepted.

The Voices scenario thus meets France's objective of fulfilling its energy needs on the basis of a reliable, sovereign mix compatible with its climate and environmental commitments and with its principles of national and international solidarity.
It strives to offer the strongest possible guarantee of achieving the goal of carbon neutrality by 2050 and delivering reliable, low-carbon electricity to everyone, at all times, no matter the weather: a guarantee from the France of today to the France of the future.

Installed capacities by source

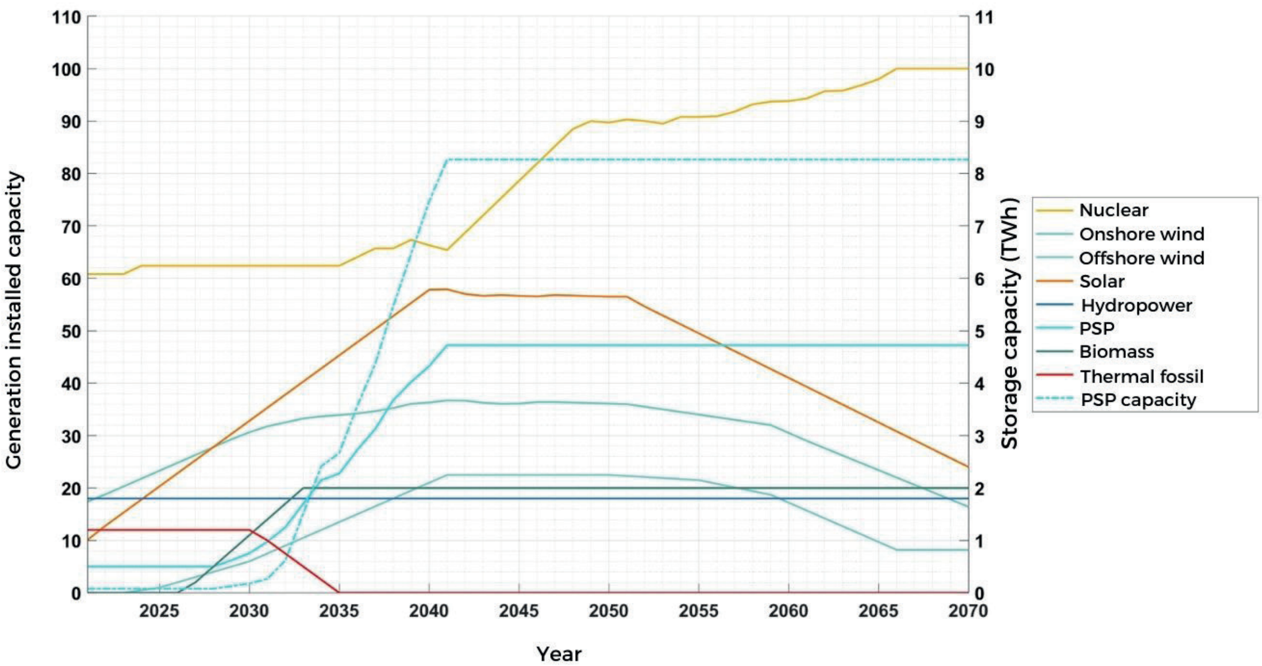


Fig.3.- Variations in installed capacity for the various primary sources of electricity required to achieve carbon neutrality by 2050 and a stable low-carbon electricity system from 2065

Scope taken into consideration: this scenario considers mainland France excluding the non-interconnected zones which include Overseas France and Corsica. Discussions on the energy decarbonisation pathways of each of these particular regions are underway and will form the subject of a dedicated report.

I Deployment in 4 phases

The scenario is divided into four main phases corresponding to the three decades from now until 2050, and to the period that will follow.

Deployment phases

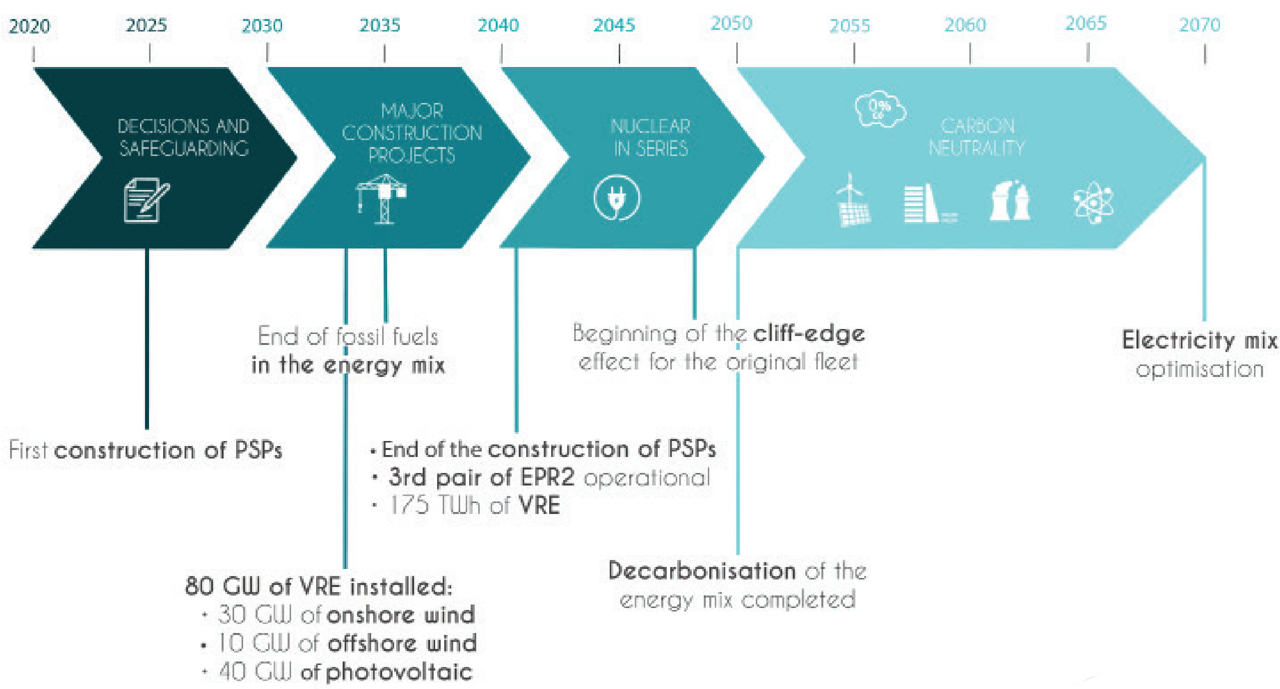


Fig.4.- Breakdown of the scenario into phases, allowing a transition from an energy mix with almost 80% fossil fuels[10] to an energy mix with ~75% low carbon electricity. VRE - Variable Renewable Energy

10 In 2022, the French final energy mix is made up of barely ~22% electricity. Electricity is the key vector in the decarbonisation of uses.

1 2020-2030
Securing the low-carbon supply

Securing the supply, optimising the existing network, accelerating the deployment of VRE[11], launching of large hydro construction projects, pouring of the first concrete for EPR2s.

Electricity generation 2025

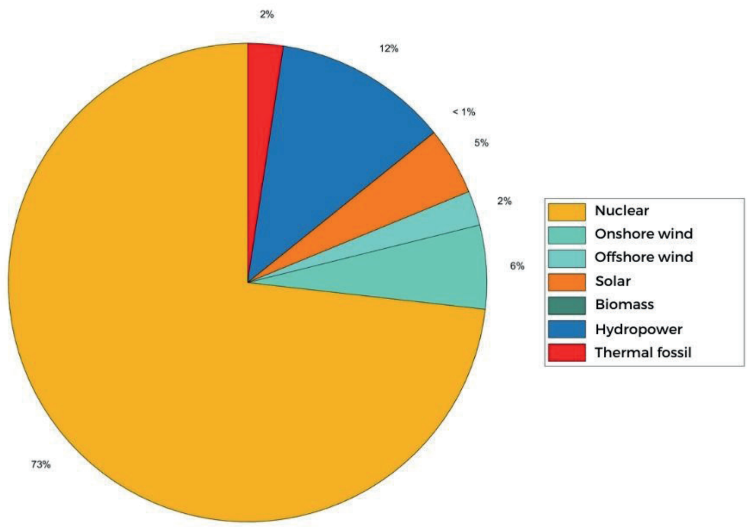


Fig.5 -. Electricity mix in 2050 according to the scenario pathway: nuclear power is slowly returning to its availability level prior to the "Grand Carénage" major refurbishment project, and VRE are encroaching bit by bit on gas but are hampered by frequent peak shaving due to a lack of synchronous consumption. In the reality of the European electrical system, a large proportion of this surplus would be exported.

Given the electrical system's current situation in terms of dispatchable capacity, the availability of the nuclear fleet and the development of VRE, with a political stance[12] of relying on imports to make up for shortfalls and, lastly, considering the time required for today's decisions to become functional infrastructures, **it has to be acknowledged that this decade will mostly be a period of insufficiency.**

With this in mind, the 2020-2030 period will mainly be dedicated to:

- **securing a supply that is as low-carbon as possible,**
- **making decisions and launching construction projects that will bring the target energy mix to fruition during the following decade.**

11 Here we are referring to VRE, mature intermittent electrical renewable energy sources, which are onshore and offshore wind turbines and solar photovoltaics.

12 RTE 2050, Chapter 7: guaranteeing supply security, p.286

From the point of view of consumption, the Voices believe that it would be premature - and risky - to implement excessive ambitions in terms of the **electrification of end uses** during this period, given that the adoption of electric vehicles is already on a very strong growth trend. France should not take the risk of electricity demand exceeding supply that has been struggling in vain to keep pace over the past decade (2010-2020). However, the 2020-2030 decade is particularly well suited to the implementation of **energy efficiency** measures: thermal renovation of residential buildings, replacement of existing resistance heaters with heat pumps to reduce the heat sensitivity of the grid, etc.
From the point of view of **supply,** there is now a ban on construction of fossil fuel power plants, and supply security will primarily be achieved through the installation of new combustion turbines operating with biomass and reserved for peak hours. **For the last 10 years, the development of wind and solar PV has continuously increased at a rate above average, from 1 to approximately 2.5 GW/year for both wind and solar individually.**

The planned **development of pumped-storage hydropower** begins in 2025 so that the smallest and most advanced projects (e.g. Redenat) can be commissioned at the beginning of the 2030s, and the largest between 2035 and 2045.

The **availability of the nuclear fleet** is increasing slowly following completion of the “grand-carénage” major refurbishment project. The increase in nuclear power generation in conjunction with the expansion of wind and solar power is gradually reducing the proportion of gas in electricity generation. The programme to extend and renew the nuclear fleet would then begin. Construction of the first three pairs of EPR2 reactors required to run in the supply chain would begin in 2026-2027 and the second in 2029-2030, in keeping with EDF’s current plans.

STAKES

SOVEREIGNTY

- System designed to allow a “self-sufficient France” situation which is **not dependent on electricity imports** from neighbouring countries, thereby guaranteeing the quantity and quality (low carbon footprint) of the electricity consumed by French citizens.
- **Large-scale re-industrialisation** to bolster economic sovereignty and reduce the carbon footprint of the manufactured goods we consume.
- Choice of hydro- and nuclear power;
  - **Sovereignty over technology and core skills,** by using technologies whose value chain is mostly located in France,
  - **Limitation of the requirement for critical metals,** which are all imported except of what is recycled, through the choice of dense and low-tech energy sources,
  - System with a high share of dispatchable generation, marginally affected by the vagaries of the weather, and resilient to climate change.
  - A system that is complementary to what can be forcast in the neighboring countries, allowing greater added value to be sought from exports.
- **Abandonment of fossil gas,** which emits high levels of greenhouse gases and the use of which is detrimental to energy sovereignty.
- **Biogas reserved for non-electricity uses with high added value** and/or off-grid, in order to limit the pressure on biomass resources, and impacts on the environment, methane emissions and our food sovereignty.
- **Ultimate peak demand met with** biomass combustion turbines, fuel for which comes from unavoidable waste sources.

2. 2030-2040
Roll-out of large construction projects

Commissioning of the main PSPs, sustained pursuit of VRE deployment, extension of the original nuclear fleet's life span to 70 years on average, commissioning of the first EPR2s, reinforcement and extension of transmission networks.

Electricity generation 2035

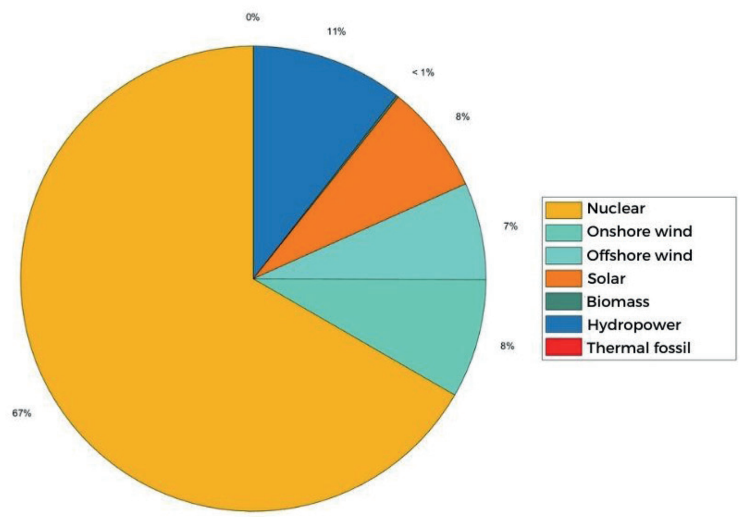


Fig.6 -. Status of the electricity mix in 2035 following the scenario pathway: since nuclear capacity has not changed, its share in the overall mix is decreasing slowly. With the gradual implementation of new PSPs*, RES generation is increasingly finding domestic outlets, but, some of this output is in fact exported, greatly benefiting the energy transition on the larger scale of the European grid. It should be noted that the last gas power plants will close in 2035.

The final mix is beginning to take shape with the commissioning of the first "new generation" facilities (because nuclear power plants and existing dams already fulfil the conditions described) which have long lifetimes, high resilience, proven technological maturity, robust production, and, of course, a small carbon footprint.

Roll-out of VRE is continuing at a fast but realistic pace[13] to accompany the electrification of end uses and ensure that decarbonisation is maximised. The capacities installed in 2035 are respectively:

- 33 GW for onshore wind,
- 13 GW for offshore wind,
- 41 GW for solar PV.

13 The paces of roll-out are compatible with the paces in the RTE scenarios: N03 for onshore wind and solar PV, and N1 concerning offshore wind.

These **are positioned at resource hotspots and, whenever possible, as close as possible to pumped-storage sites** (in the case of facilities that will remain in the long-term), (see map in Fig. 25, p 37 of this document). Their purpose is to power the reservoir filling operations, so as to limit the impact of their intermittent nature on grid stability and limit their proportion within the mix to reduce the associated infrastructure required, optimising overall costs. Storage of the electricity they generate in association with PSPs allows them to contribute to supply security and the country's electrical independence without destabilising either the grid or the electricity market.

Half of the pumped-storage capacity, i.e. 20 GW, is expected be in service in 2036, and the full capacity in 2043.

Simultaneously, the oldest reactors in the original nuclear fleet will be undergoing their sixth 10-yearly inspection. Construction is expected to begin on the 3rd pair of EPR2s in 2031.

For the 4th pair onwards, construction will occur at a rate of two new units per year. Commissioning of the first pair of EPR2s is expected between 2035 and 2036, the second pair between 2037 and 2038, and the third in 2041. The power of the EPR2s compared to the current generation facilities they are gradually replacing maximises use of existing nuclear sites and limits the need for new ones, thus improving their already excellent environmental credentials.[14]

Fossil-fired generation continues to decrease in the first half of the decade. **Decommissioning of the last true gas fossil fuel generation units is expected for 2035.**

14 Refer to the UNECE's meta-analysis entitled "Life Cycle Assessment of Electricity Generation Options". 2021, United Nations. https://unece.org/sites/default/files/2021-10/LCA-2.pdf

3. 2040-2050
Achieving the objective of total decarbonisation

Cruising speed for deployment of EPR2s, commissioning of the last PSPs, stabilisation of VRE, the start of decommissioning of the original nuclear fleet.

Electricity generation 2045

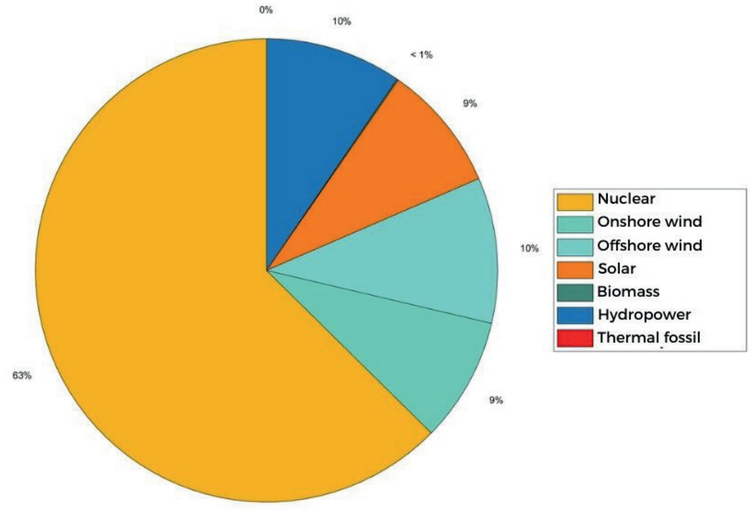


Fig.7 -. Status of the electricity mix in 2045 according to the scenario pathway: the nuclear share increases slowly as new reactors come on-line. The wind and solar fleets are no longer expanding, but are maintained and optimised at least until carbon neutrality is reached in 2050. The PSP fleet is fully operational and fulfilling its role of securing supplies during times of peak demand.

During this decade **the objective of total decarbonisation of the French energy mix is achieved** in conjunction with securing the supply in a context of high levels of electrification, strong re-industrialisation[15] and a return to energy independence.

However, it still cannot be considered environmentally optimal. This objective will not be achieved until the following decade with, firstly, the gradual replacement of third-generation nuclear reactors with reactors of a more advanced design enabling a highly-optimised fuel cycle, and, secondly, the gradual reduction in the contribution from intermittent energy sources which have a large land footprint, a relatively short lifetime, and consume substantial amounts of natural resources. The mix is therefore yet to be stabilised.

Whilst the trend initiated during the previous decade will continue in the 2040s, this new decade will see the emergence in particular of new generations of tried-and-tested technologies, which will be integrated as their state of development allows.

15 We retain RTE's definition as given in their chapter 3 "Consumption of reference scenario N03", i.e: "a clear reversal of the current trend in industrial development, consisting in halting the long-term de-industrialisation process and in stabilising the manufacturing industry's share in GDP at approximately 10% in 2050. Maintaining the industry's share of GDP at 10% therefore already presents itself as an industrial redeployment strategy in France, in line with the public policy goals of relocating some imports and stimulating industrial development in certain strategic sectors. This scenario goes against the current trend but is entirely achievable; it represents in itself an effort to re-industrialise the country."

The scenario does not rely on these new technologies as the default, in particular those that involve nuclear energy input [16]. Nevertheless, they will be welcome once their performance, safety, applicability to the various uses and feasibility for development at an industrial scale (including a materials life cycle assessment) have been demonstrated.

These new nuclear technologies will also pave the way to subsequent industrial applications and other energy uses within France (transport, seawater desalination, heating networks, etc.) to which nuclear power could provide a direct low-carbon solution other than by means of electrification.

STAKES

RE-INDUSTRIALISATION

- Installed electrical capacity compatible with significant re-industrialisation of the country at competitive energy costs.
- Contribution to decarbonisation of the global economy.
- Support for economic activity, employment, and for encouraging growth nationwide via the uniform distribution of reliable, low-carbon and cheap electricity in the long-term.

In real terms, this decade would involve:

- Commissioning of two EPR2 nuclear units per year from 2041, bringing the total number of new EPRs to 22 in 2050[17].
- An acceleration in electrification of end uses, made possible by the strong increase in generation capacity.
- The end of expansion of the VRE generation fleet, with the responsibility of increasing generation handed over to the new nuclear fleet.
- Decommissioning of the first nuclear reactors from the original fleet in 2048, beginning with unit 1 of the Dampierre power plant at the age of 68.
- In 2050, the economy is almost fully electrified, and carbon neutrality has been achieved.

16 Including foreign technologies

17 In its response to the 2050 "Energy Futures" consultation, EDF indicates that it has the capacity to construct one unit per year on average between 2035 and 2050 based on the sector's current capacity.

STAKES

ENVIRONMENTAL IMPACT

- Priority placed on rapidly achieving a low-carbon energy mix. Abandonment of fossil energy sources: coal, oil and gas.
- Limitation of greenfield land loss:
  - limitation of the use of biomass to its unavoidable portion (organic waste, crop residues for human and animal food, construction wood offcuts, etc.),
  - choice of high-density energies - therefore with a small land footprint (hydro- and nuclear power),
  - Priority to offshore and onshore wind energy.
- Limitation of outdoor and indoor pollution, by prioritising (but not exclusively) electrification over the extensive use of wood energy for residential heating.
- Limitation of the use of critical metals and minerals and their extraction;
  - wind and solar energy limited as far as possible to uses which do not require batteries, digital equipment such as smart grids, interconnection cabling, etc.
  - hydrogen production limited to stationary uses located close to demand, to limit the requirement for batteries, dedicated networks, and transformers,
  - priority placed on PSPs rather than batteries for electricity storage,
  - in the nuclear sector:
    - o uranium recycling,
    - o transition to EPR2 technology to limit uranium consumption per kWh of electricity generated,
    - o accelerated transition to 4th-generation nuclear technologies, thereby leading to adoption of a closed nuclear fuel system.

4. After 2050
The transition to a long-lasting low-carbon economy is complete

Electricity generation 2055

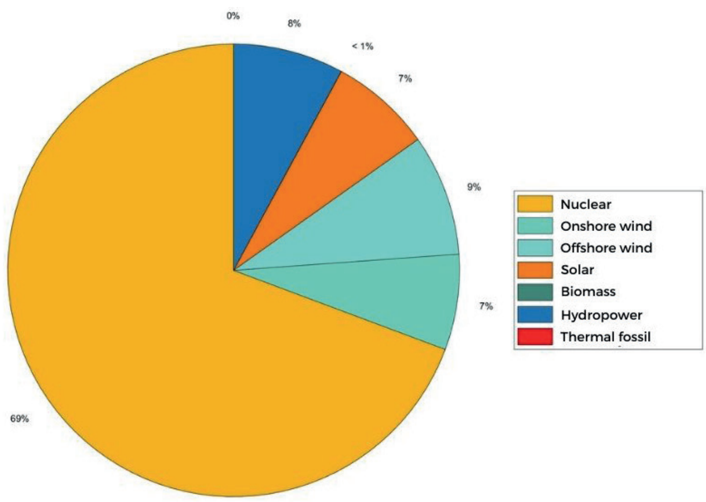


Fig.8 -. Status of the energy mix in 2055 according to the scenario pathway: the nuclear share continues to increase but at a slower rate; growth of the fleet slows down as the new reactors compensate for gradual decommissioning of the original fleet. VRE capacity decreases slowly as and when the facilities reach the end of their working life. Since carbon neutrality has now been achieved, it will be possible to optimise the energy mix on the basis of other criteria without endangering climate-focused targets.

The fundamentals of the French energy mix are stabilised. Consumption levels are stabilised, while energy efficiency and lifestyle changes are absorbing any extra demand related to population and economic growth. The technological choices made ensure the highest possible levels of longevity and environmental sustainability in terms of current physical and technological knowledge.

The energy transition is not "only" low carbon, it also becomes ecologically sustainable and beneficial for humanity.

Not all issues have been definitively resolved; the renewal of facilities, control and regulation of activities, pollutant capture, and treatment and recycling of all waste categories, will remain targets for technical progress and governance. But none of these will be as threatening and insoluble for the entire planet and humanity as our current energy systems and the paths they are following. We already have solutions for all these issues . They require further improvements, but this can be done by using skills we possess, based on physical principles we fully understand.

VRE begin a phase of contraction to a relatively low but stationary level, consisting in retiring some of the least profitable capacities when they reach the end of their working life[18].
The primary function of this permanent top-up capacity is to continue complementing baseload nuclear power generation by coupling VRE with PSPs to absorb demand variability, during peak periods in particular, instead of implementing load following which would distance the nuclear fleet from its technical and economic optimum. Alternatively, this top-up capacity may be replaced with similar enhanced technologies, or with other nuclear or geothermal technologies that are better suited to this specific need than high-power reactors.
By reducing this VRE top-up capacity to the minimum necessary, these low-carbon, rapidly deployable, and geographically adaptable electricity generation capacities can be reserved for the decarbonisation of countries elsewhere in Europe and around the world that are still in transition, where fossil energy sources still dominate and nuclear technology is insufficient, emerging, and absent in the long-term.
By decommissioning infrastructure without renewing it, a relatively large quantity of metals, including some that are critical, can also be reintroduced into the industrial circuit through recycling, at a time when they may be even more critical than they are now.

By 2050, France will benefit from an energy mix that emits very low levels of greenhouse gases and will be capable of keeping pace with the electrification of end uses. The aim of this mass electrification is to decarbonise all other emissions sources while bolstering re-industrialisation.
By revitalising its industrial sectors on the basis of reliable and proven technologies in which it has full expertise, France will also greatly increase its economic, energy and industrial sovereignty.
This energy supply security will ultimately have been gained alongside and in support of fair access for all to electricity and to everything this allows.

18 The average lifetimes of intermittent electrical energy sources (onshore, offshore and solar) are 20 to 30 years. Precise estimation: Costs and profitability of renewable energies in mainland France, CRE [2014]

Roselend Dam. France P.

II Consumption

An upward trend, driven mainly by industry and transport, but with marked variability due to heating.

The aim of the Voices energy scenario is to phase out fossil fuels (and, if possible, biomass) as extensively and as quickly as possible, by means of electrification.
Electrification will have to be ambitious if it is to achieve the goal of carbon neutrality, but will also have to be reasonable: the pace of implementation must be aligned with the capacity of the generating facilities to meet this additional demand for electricity.
Confusing speed with haste and forcing certain sectors to electrify their processes too quickly would lead to a risk of having to keep existing fossil-fuel power plants (most of them gas-fired) in operation, or even having to open new ones with a longer lifetime, thereby undermining the objectives of reducing greenhouse gas emissions.
The last fossil fuel-powered power generation facilities are due to be decommissioned in 2035.

Three major and two minor consumption categories are taken into particular consideration:
- industry
- road transport
- heating for buildings
- domestic hot water
- food cooking.

We have opted to consider a like-for-like assessment, without making strong assumptions regarding potential reductions through improved energy efficiency and conservation. **Electricity consumption is expected to increase from 480 TWh/year (of which 30 will be lost) in 2021, to just under 800 TWh/year (of which 50 will be lost) in 2050.**

Variations in electricity consumption by sector

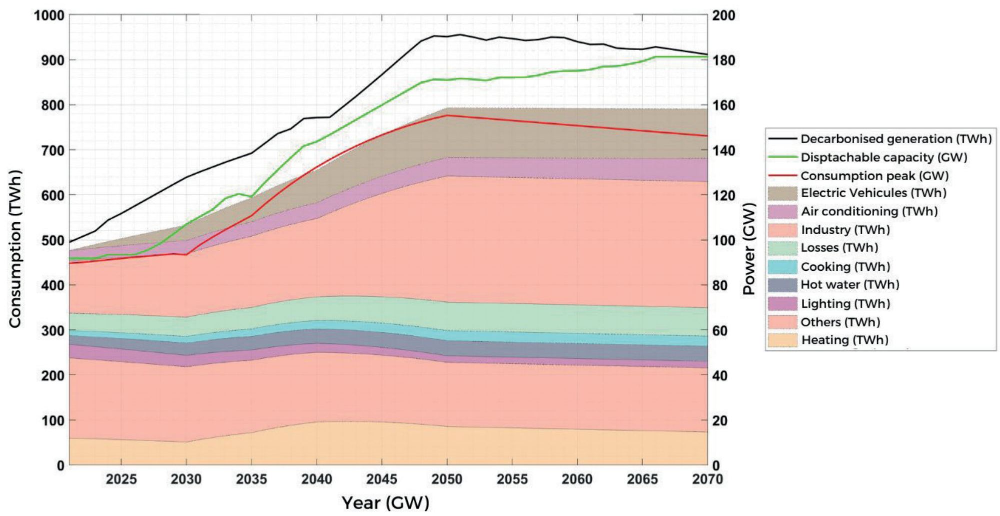


Fig.9 - Variations in consumption by sector over the period covered by the Voices scenario, between 2022 and 2070, according to the assumptions defined. Consumption is driven upwards by the particularly high level of electrification, which is necessary for the decarbonisation - vertical (reindustrialisation) and horizontal (uses) - of the French energy mix.
The complete system has a margin of about 10% in terms of power and annual production capacity.

1. Industry

Industrial electricity consumption will increase from 115 TWh/year to 280 TWh/year.

The profile of industrial electricity consumption should remain relatively unchanged from today, in other words within a relatively constant range that decreases slightly at weekends.
The target value of 280 TWh/year is consistent with that adopted by RTE[19] of 180 TWh/year, except two choices which explain this difference:

- almost 100% electrification of industrial processes to eliminate as much biomass as possible, compared with 70% in the case of RTE,
- production of hydrogen for industry (~25 TWh), considered as being solely for industrial use.

Indeed we wish to **avoid developing a complete integrated system for producing, transporting and storing hydrogen.** We consider that industrial firms that need hydrogen for their processes will produce it themselves using low-carbon electricity whose supply will be guaranteed based on their needs..

19 RTE, "Energy Futures 2050" study (in French), Chapter 3, "Consumption"

2. Road transport

This consumption is divided into 75 TWh for light-duty vehicles and 35 TWh for heavy-duty vehicles.

The profile of consumption by electric vehicles, which currently represents a tiny fraction of the total electricity demand, will have two components by 2050:

- Marked night-time consumption for light-duty vehicles, which could, in summertime, be partly shifted to the middle of the day,
- Fairly constant daytime consumption for heavy-duty vehicles, which will correspond to HGV (Heavy Goods Vehicules) traffic on motorways.

Overall, electricity consumption for road transport would increase from almost 0 to 110 TWh/year.

While this scenario may seem timid as regards **demand management,** it takes the liberty of shifting light-duty vehicle charging to three hours later than what might be considered a "natural" charging period, in order to make better use of the night-time drop in overall consumption.

In summer, on the basis of a much more resolute development of demand management, light vehicle recharging could, if necessary, be shifted to the middle of the day to take advantage of the abundant solar power generated without posing a constraint for supply security. The latter is ensured by the very high degree of flexibility provided by pumped-storage hydropower and by the substantial margins available at this time of the year.

As regards HGVs, this scenario considers that road freight will be almost completely electrified, particularly through the electrification of motorways (through overhead contact lines or similar means)[20]. This will make it possible to:

- free up as much biofuel, and therefore biomass, as possible for other more critical uses (air and sea transport, military, etc.),
- **limit the need for high-capacity charging infrastructure** for voluminous batteries on trucks, which would be charged while being driven,
- **limit the size and weight of batteries installed on trucks,** thus reducing the power consumed at constant loads and drastically reducing the quantity of metals needed to manufacture them.
- While it is highly desirable and something we strongly encourage, the scenario does not yet factor in **a massive modal shift of road freight to the railways.** This would reduce the electricity consumed per tonne-km transported by a factor of between 4 and 5. We consider that the drop in consumption brought about by shifting 50% of road freight to the railways would be between 13 and 15 TWh/year less than that obtained through the electrification of trucks with a constant modal share.

20 "Vergleichende Analyse der Potentiale von Antriebstechnologien für Lkw im Zeithorizont 2030" study
Electrifying motorways for HGV traffic is an option being seriously considered by several countries. In Germany, for instance, the federal transport ministry recommends electrifying one third of the country's motorway network (i.e. ~4000 km), while continuing to invest in rail freight.

FAIR ACCESS TO ENERGY

STAKES

- Reasoning in terms of making France self-sufficient ultimately enables it to contribute to energy solidarity within the EU.
- By not renewing VRE facilities at the end of their working life, we free up industrial capacities and essential resources in this area for countries who would need them more than we do to reduce their carbon footprint.
- Maintaining a "public service" approach to electricity: at present electricity is the only service in France, along with stamps and the interest rate on "Livret A" savings accounts, that benefits from a regulated tariff and is accessible to everyone regardless of their location, social status or financial resources, thanks to the centralised and optimised nature of nuclear power combined with hydropower.
- An energy scenario whose viability does not depend on imposing strong constraints on the population in terms of demand management and flexibility.
- A limited price per kWh, by:
  - limiting installation and renewal costs by maximising use of existing low-carbon power generating technologies, equipment and facilities,
  - extending the working life of existing and future facilities, especially wind and solar power plants and nuclear reactors (EPR2).
- Limiting conflicts of use: land use limited by only using unavoidable biomass and choosing high-density energy sources (hydro, nuclear) and therefore reducing impacts on other human uses, notably agriculture.

3. Heating

Heating is also a major point of attention, but much more for the power demand it generates than for its gross consumption.

For thermal consumption related to the heating of building in France - currently 400 TWh/year - we assume that a 30% reduction will be achieved by making buildings more energy-efficient.

Electric heating will increase from 55 TWh/year - consumed mainly by resistive systems - to 86 TWh/year through electrification by distributed or centralised heat pumps operating in conjunction with heating networks.
This consumption may be reduced in future updates by taking into account the potential from geothermal energy and cogeneration.
The assumed reduction in thermal consumption related to heating corresponds to an improvement in thermal performance of 30% by 2050 over 2020 levels, which is slightly less ambitious than the 40% improvement assumed by RTE and in keeping with the results obtained over the past 30 years. This value will nevertheless require strong support from the building sector in order to successfully implement the renovations it entails, while leaving more room to manoeuvre.
Lastly, about 10% of the heat produced by electric heating will continue to come from resistive systems, consuming about 23 of the 86 TWh/year.

Use of biomass heating fuels would be halved, from 80 to 40 TWh/year, through improvements in the thermal performance of homes using these fuels as well as by doing away with open fire. The use of wood will be reserved mainly for homes that are not suitable for heat pumps or that cannot be connected to a district heating network, or else as additional heating on extremely cold days to limit demand for electric power.

4. Domestic hot water

Domestic hot water requires 60 TWh of heat each year, one third of which is currently provided by electric water heaters.

By generalising thermodynamic water heaters so as to increase their market share to about two thirds of hot water production, **it is possible to electrify this sector completely** while only increasing electricity consumption by 13 TWh/year.

Without requiring the user to make any changes, this consumption is shifted from night-time slots to the very early afternoon to take advantage of solar power production when it is available, the night-time slots being reserved for charging electric vehicles.

5. Food cooking

Lastly, the power consumed in food cooking will increase from 11.5 TWh/year to 23 TWh/year as gas cookers are replaced with glass-ceramic or induction models.

Supply-demand balance during a winter week in mainland France

Consumption by sector

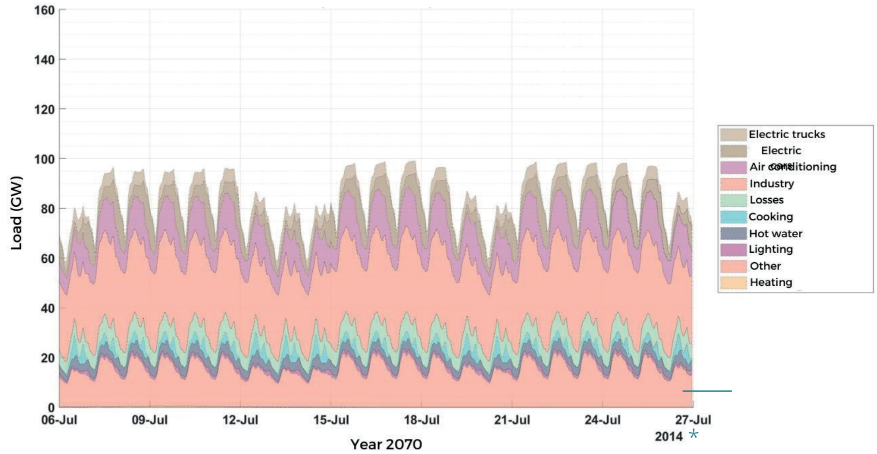
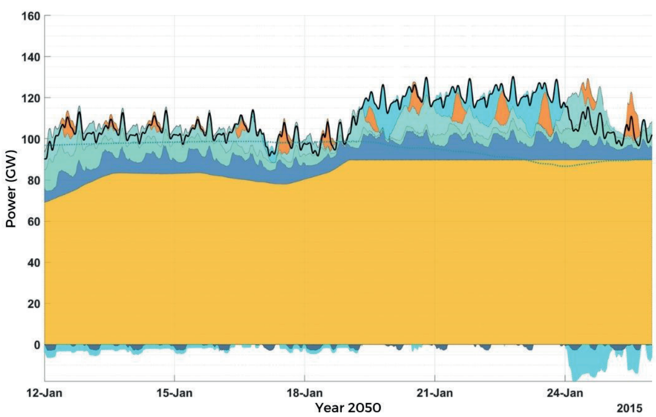


Fig.10 -. Electricity consumption profile by sector during a typical winter week in mainland France
Electric vehicle charging is pushed back three hours to make better use of the night-time drop in consumption.

Normal winter week, 2050



Very cold winter week, 2050

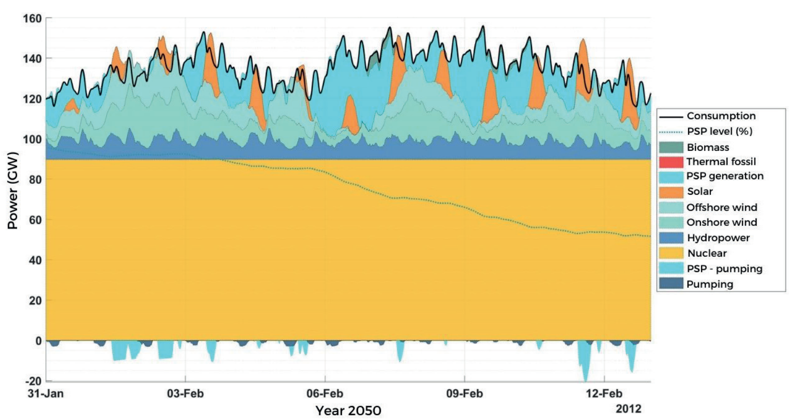


Fig.11 - Generation profile of a typical winter week in 2050. Nuclear power plants are operating as base-load plants at maximum capacity. PSPs, hydroelectric dams (and, on the margins, biomass combustion turbines if demand is very high) are keeping pace with demand, especially during phases when output from VRE is limited.

Fig.12 - Generation profile of a design-critical winter week in 2050, with transposition of the cold spell of February 2012. PSP turbines are operating at maximum capacity with backup from biomass combustion turbines to make up the power shortfall and slow down the reduction in water stocks.
At peak times, the system has a power margin of about 10% excluding interconnections.

*The years indicated at the bottom right of each graph correspond to the benchmark meteorological years

Supply-demand balance during a summer week in mainland France

Consumption by sector

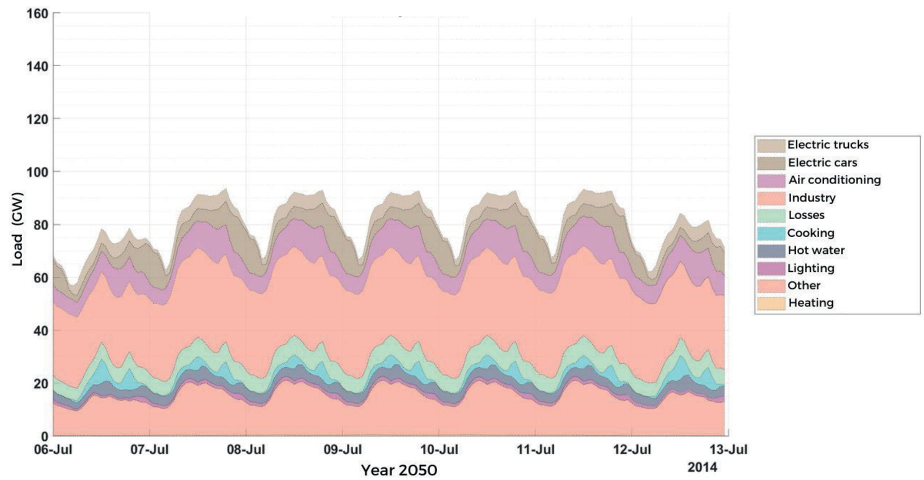


Fig.13 - Electricity consumption profile by sector during a typical summer week.
In this case, there are no restrictions on EV charging and only water heating is shifted to the daytime. Peak consumption coincides with solar noon.

Normal summer week 2050

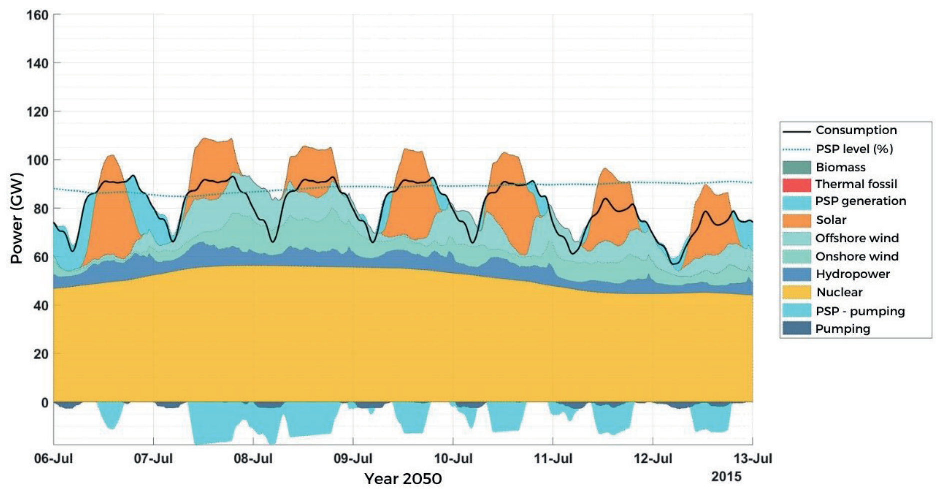


Fig.14 - Generation profile of a typical summer week in 2050. The modulation of nuclear power generation is limited to a few MW/min, and hydropower plants/PSPs are keeping pace with demand. Solar power is used to fill the PSPs during the daytime.

III Generation facilities

The various power generation facilities that have been or will be installed, renewed or extended will play differing roles in the system projected for 2050 and beyond. The merit order on the grid as presented here ranks the different sources of energy on the basis of price and is designed to maximise the potential of each in light of its benefits and drawbacks and depending on demand.

Merit order on the grid

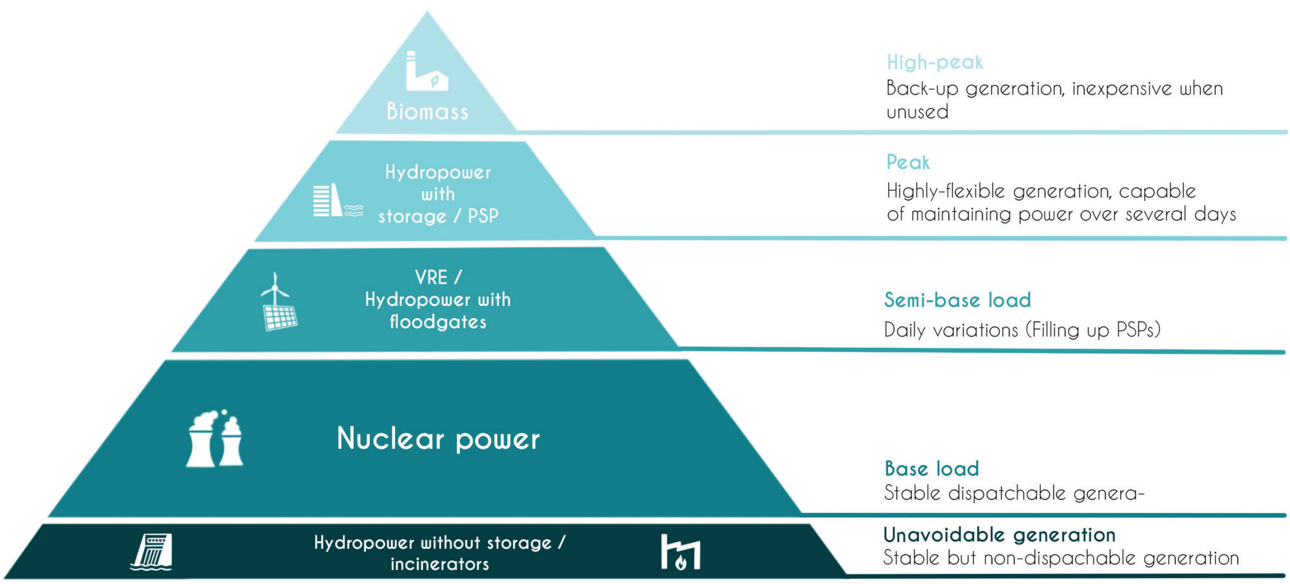


Fig.15 - Role of each power generation source, from those called on permanently to meet base-load demand (at the base of the pyramid) to those used to meet peak demand (at the top).

1. Existing nuclear power plants

Extending the lifetimes of all these plants to 70 years is both necessary and technically feasible. It must, however, be planned for.

Changes to the original nuclear fleet

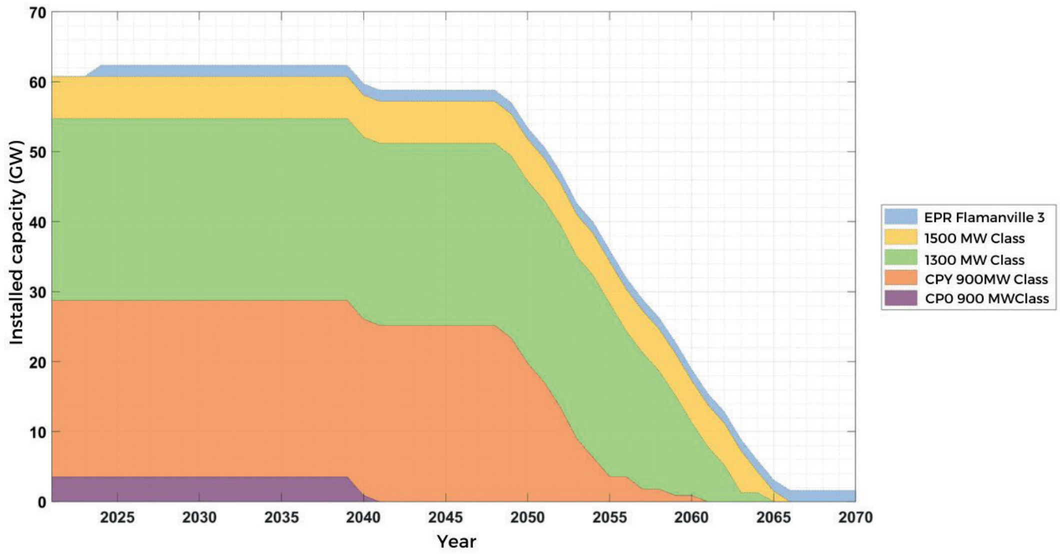


Fig.16 - Cliff-edge effect of the original nuclear fleet according to the Voices scenario (middle scenario of closure at 70 years, details in fig.16), in keeping with available international data on reactors of similar design and the assessments of the French Nuclear Safety Authority

To keep the proportion of nuclear power at around 70% of the electricity mix in 2050, with consumption potentially increasing to 800 TWh/year, nuclear fleet capacity must remain higher than 80 GWe.

.

Reviving the reactor construction industry, supported by a strong political desire to keep nuclear power as a central pillar of the country's energy strategy, will make it possible to deploy about 24 new operational units by 2050, or about 40 GWe.

To reach the necessary level of 80 GWe without forcing the construction of new reactors at an unrealistic pace, about 50 GWe must be retained on the original fleet until at least 2045. Maintaining this capacity will mean pushing the start of the cliff-edge effect back from 2040 to 2048 and organising the decommissioning of generating units in a linear fashion so as to reach a relative power plateau as of 2050, once consumption has stabilised.

Assumption of shutdown at 60 years

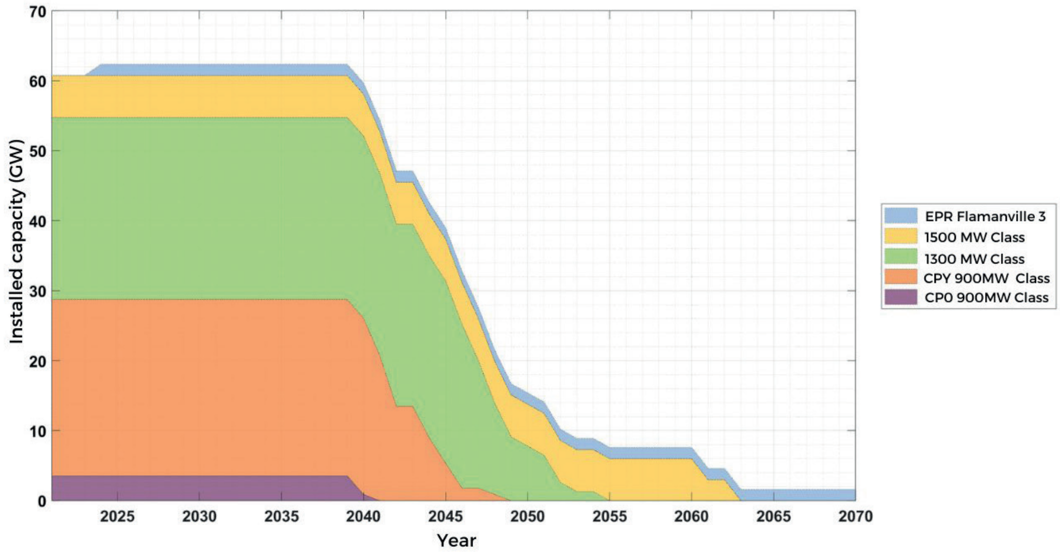


Fig.17 - Cliff-edge effect of the original nuclear fleet with closure at 60 years, as adopted for EDF's baseline assumption

Almost the entire fleet will hence have to be extended beyond 60 years, with the exception of the CP0 plant series (Bugey)[21], which could be decommissioned during its sixth 10-yearly inspection, in other words upon reaching the age of 60. The average age reached by the reactors of the existing fleet upon closure (excluding Fessenheim) would hence be 69 years, with a minimum of 62 and a maximum of 72.5.

Six units of the current fleet would be extended by 1 to 2 years without a seventh 10-yearly inspection, as was the case with the two Fessenheim units, which were able to operate in total safety for more than 2 years after the theoretical date of their fourth 10-yearly inspection because their shutdown had been anticipated very shortly thereafter. Statements made by the safety authorities and the industry suggest that such an extension is technically feasible, and it is simpler and quicker to keep operating an existing reactor than to build a new one.

Saint-Alban nuclear power plant, France

This will have to be prepared very early on, however. While critical components such as tanks, vessels and containment structures do not currently pose any particular problems, the management of ageing and the replacement of large metallic components on the primary circuit or backup circuits must be properly anticipated[22]. We must avoid situations such as a part being out of stock, or a component with a 30-year lifetime

21 The Bugey reactors will be the only ones in their series, so it could prove much more costly to extend them than the other 900 MWe reactors. If extending their operation proves too costly, and the margins on the grid are sufficient, this will not take place.

22 Cf. Testimony of the chairman of the French Nuclear Safety Authority for its annual report to the French Parliamentary Office for Scientific and Technological Assessment (OPECST) in May 2022. The decision to extend beyond 60 years must be made by 2030 so that the studies can be prepared and the results made available early enough to anticipate the risk of this not being possible for some reactors.

needing to be replaced when it will be used for only five years before the reactor concerned is decommissioned.

For this reason it is important to give the operator a clear view of the future by deciding whether to extend the nuclear fleet beyond 60 years as early as possible.

French President Emmanuel Macron's announcements in February 2022 that units would not be closed on grounds other than safety are a step in the right direction.
At present it seems increasing likely that the original fleet will be at least partially extended beyond 60 years, given how far behind the French government has fallen in making energy choices (in respect of nuclear power as well as VRE and energy storage).

Age of units at final shutdown

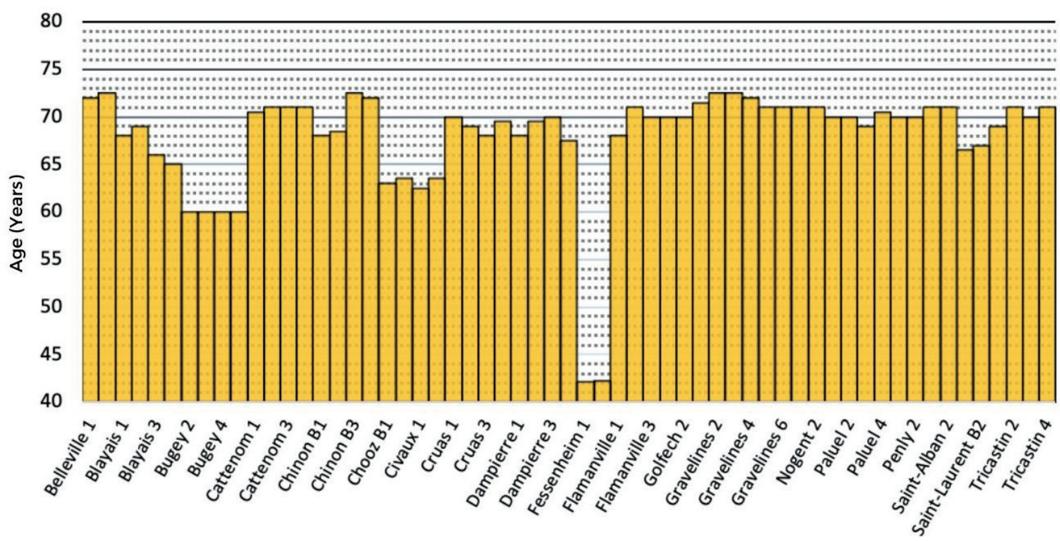


Fig.18 - Age at which reactors in the original nuclear fleet are closed according to the Voices scenario, proposed in light of available international data on reactors of similar design and contingent on the opinion of the French Nuclear Safety Authority

2. New nuclear power plants

Industrial prospects in the 2040 time frame remain uncertain and depend on visibility and political stability for the industry

Installed capacity of new nuclear power plants

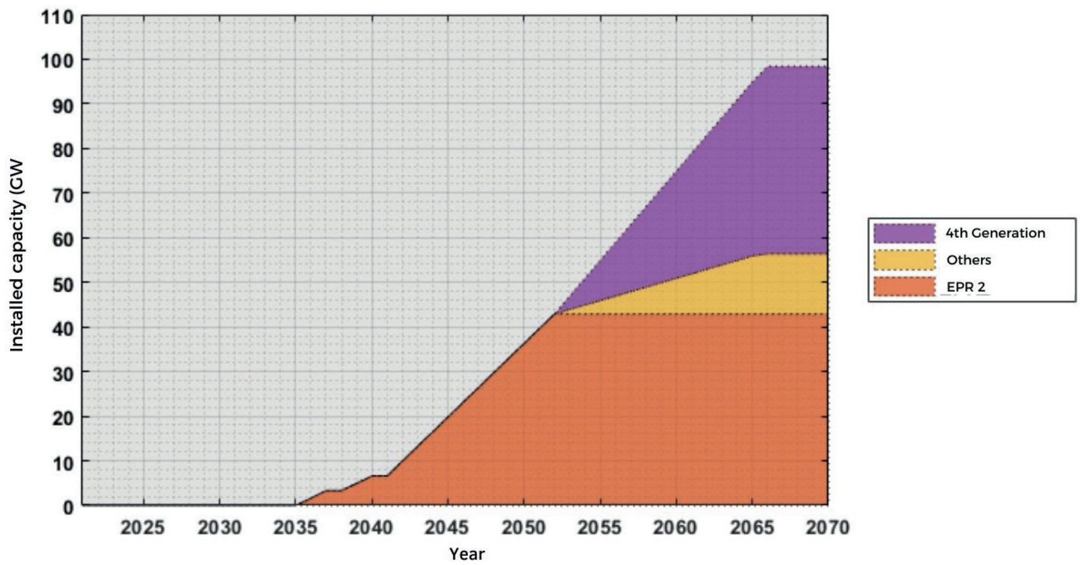


Fig.19 - Variations in installed capacity of new nuclear power plants, factoring in the gradual ramp-up of the reactor construction sector

In line with the consensus among nuclear industry experts, the scenario considers that the rate at which new reactors are built post-2040 will be highly dependent on political and industrial visibility for ongoing nuclear energy development in France.

Voices of Nuclear are well aware that **the French industry does not currently have the conditions, industrial capabilities, workforce or methods for the task it is expected to fulfil in terms of renewing the country's fleet, let alone extending its operation.** All the parties involved recognise that it will take between 10 and 15 years for the industry to rebuild and strengthen its facilities, recruit new staff and equip them with the skills required to construct new reactors on a large scale. The French nuclear industry needs to relaunch its production capacities, which is why it is essential to start renewing the fleet with the three pairs of EPR2 reactors proposed by EDF: a first pair from 2026 to 2035, a second pair from 2030 to 2038, and a third from 2033 to 2041.

Once these three projects have been launched, and provided that the industry continues to enjoy the long-term visibility it needs, construction will be able to continue at a rate of two units per year as of 2035, with commissioning taking place at the same rate as of 2041.

In these conditions it will be possible to commission up to 22 new EPRs by 2050, increasing the total capacity of the nuclear fleet to 90 GWe.
To meet the need to diversify nuclear power generation and prepare for the arrival of fourth-generation reactor systems, other types of reactor are to be developed

in parallel with the EPR2s, such as, potentially, small modular reactors (SMRs). It is estimated that 3 to 4 GW generated by these other reactors could be online by 2050.[23]

23 Assumption made by RTE but not design-critical in the scenario studied here.

STAKES

RENEWING THE NUCLEAR FLEET

Reviving the French nuclear industry:

- Choice to reinvest in a French sector of excellence guaranteeing the country's energy and technological independence.
- Need to rebuild the industry's capacity to ensure the complete renewal, and extension, of the original nuclear fleet.
- The new nuclear reactor construction sector can achieve maturity by 2040, provided that the requisite decisions are made quickly.
- The absence of construction projects in the last 20 years is hindering the revival of construction capacity in the sector.
- In addition to potentially reusing a number of sites, there is scope for exploring new locations for the EPR2s, such as the disused oil depot at Antifer.

Technological choices:

- Choice of the pressurised water reactor, a dispatchable, safe, low-carbon technology with a limited environmental footprint, capable of reaching and sustaining a capacity of 90 GWe.
- Choice, initially, of the EPR2, a technology benefiting from extensive lessons learned from recent projects and deployable rapidly at an industrial scale.
- Prospects for diversifying the nuclear sector, with kick-starting of research programmes on generation IV reactor systems and development of other types of third- and fourth-generation reactors including SMRs.

After 2050, choices can be made freely and the time frame is too far into the future to make projections. For Voices of Nuclear, there do not seem to be any grounds for continuing to build EPR2s after that date, and it would be preferable to turn completely to one or several new reactor systems.

These systems are very likely to comprise:

- Sodium-cooled, which is already technologically fairly mature,
- Molten salt, which is technically more complex but offers more prospects in the very long term,
- Very high temperature: greater efficiency, direct applications at very high temperatures, potentially enhanced safety,
- Industrial and heating applications.

This desire to keep nuclear power as the mainstay of the electricity mix would require, as would the extension of all the earmarked units of the original fleet, a revision of the 2015 French Law on Energy Transition for Green Growth (LTECV), which still caps the installed capacity of the French fleet at its 2015 level, i.e. 63.2 GW.

Staggering of new nuclear projects in pairs

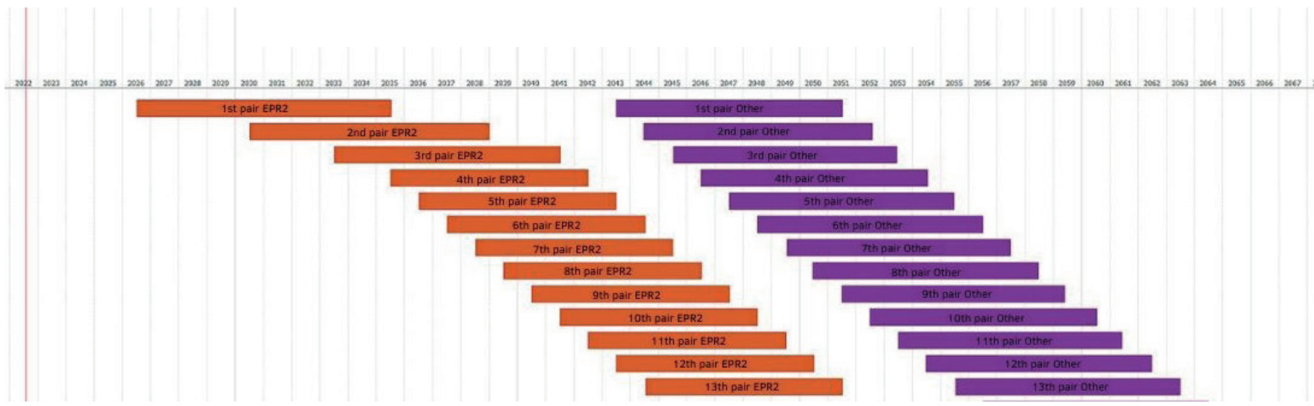


Fig.20 - Staggering of new nuclear projects in pairs, initially EPR2, then transition to a more diverse nuclear mix: Generation IV technologies, variable installed capacities (SMR etc.) and different suppliers (other than EDF), in line with expected developments in the technology and, potentially, the industry.

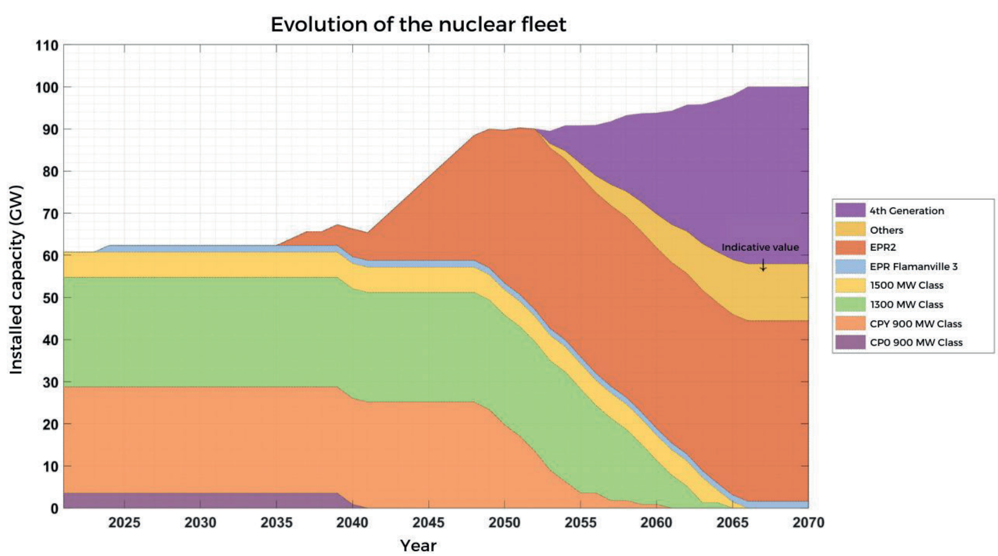


Fig.21 - Transition between the originall nuclear fleet and a new fleet based on new technologies.

3. Pumped-storage hydropower

Upper reservoir of the Grand'Maison pumped-storage hydropower scheme in Isère, SE France

This economical, reliable and efficient technology is too often overlooked in debates on energy, but is set to play a vital role in ensuring that the electrical system is flexible and robust.

The conscious choice made in this energy scenario not to consider interconnections as a design-critical aspect of normal operation of the power system goes hand-in-hand with the integration of a **substantial long-term storage capacity,** unlike RTE's scenario N03, for instance.

As a rough estimate, between 5 and 10 TWh of storage will be required. Just two technologies are technically capable of storing and returning such large volumes: power-to-gas-to-power and pumped-storage hydropower.

At present, only the latter is available on an industrial scale; setting up the complete value chain of synthetic gas (including hydrogen), including its transport, storage, distribution and conversion, remains a technological gamble, for an overall efficiency no higher than 25 to 35%.

In contrast, pumped-storage hydropower is a simple, efficient, mature and robust technology. It has been in use on an industrial scale for nearly a century, and its cycle efficiency is comparable to that of electrochemical cells[24]. All this for a cost more than 10 times lower, much smaller quantities of metals, and a lifetime of around a hundred years.

24 The cycle efficiency of the most recent pumped-storage hydropower schemes can exceed 80% and even come close to the 90% achieved by electrochemical cells. In this scenario the efficiency considered will be 75%, to take into account additional losses from very long headrace tunnels and losses on the transmission network.

This scenario provides for an additional capacity of 42 GW from new PSPs representing a total reversible capacity of at least 8 TWh[25], i.e. about a quarter of the potential topographically suitable areas identified by the Voices, spread over some twenty sites among which six require a completely new infrascture.

The French fleet of hydropower plants currently includes six PSPs, with a cumulative capacity of 5 GW and capable of storing 80 GWh in total. The distribution of this reversible capacity is very uneven, however, as some PSPs have a time constant of four hours while others can operate for nearly two days at full power.

Penstocks of a hydropower plant

The 8 TWh of new capacity required by the scenario exceed the ~6 TWh identified by the JRC report[26] of 2013, but the assumptions used in that report are much more limiting than seems applicable here.

> *Details on the sites considered, and justifications for these choices, can be found in the appendix on pumped-storage hydropower.*

Being hydraulic infrastructure, pumped-storage hydropower plants obviously have a major drawback: they have a substantial land footprint, leaving little freedom when it comes to choosing sites, and sometimes requiring the displacement of several thousand people in order to create the reservoirs.

To accommodate the 8 TWh provided for in the scenario, an estimated 250 km² of land will have to be allocated and 12,000 people will have to be rehoused and compensated.

These are large figures. However, they represent less than 10% of the land that would be required to construct the ground-mounted photovoltaic power plants stipulated in RTE's energy scenario M0 (100% RE) and two to three times less than in scenario N03 (with 50% nuclear power).

In other words, PSPs require a relatively small fraction of the ground surface compared with the area that almost all the existing scenarios propose to dedicate to VRE.

Moreover, as pumped-storage hydropower is based on water storage, it offers co-benefits of which no other technology can boast and that will probably prove indispensable in facing the consequences of climate change that will be inevitable in the second half of the century and are already being felt. The benefits of water storage include maintenance of low-flow levels in rivers, resources for agriculture, scooping points for water bomber aircraft, co-use for floating photovoltaic power plants (included in the scenario to generate 2.5 GW, i.e. 10% of the surface area of the reservoirs), and, in some cases, recreation[27].

Obviously not all PSPs will be able to perform all these functions, but it is important to bear in mind that a dam has far more uses than simply storing energy and generating electricity.

It is also important to note that more than half of the sites considered involve reusing an existing hydropower facility.

25 Any additional capacity achieved will merely make the system even more reliable and is hence welcome.
26 Joint Research Committee, Assessment of the European potential for pumped hydropower energy storage: A GIS-based assessment of pumped hydropower storage potential [2013]
27 Given that water sports activities take place mainly in the summer, a season during which PSPs are not under significant pressure in terms of depth of discharge thanks to a constant supply of solar power, the impact of the water level variations generated by the pumping and generating cycles could be minimised.

This does not mean that existing dams can be reused as they are. In many cases their level will need to be raised or they may even have to be completely rebuilt (as is the case with the Chambon site in SE France).

Advantageous as this reuse of existing hydropower facilities may be from the environmental, financial and social points of view, it does have one drawback: the lakes in question will no longer be able to serve as simple seasonal reservoirs, and their operation will have to be completely rethought. This is typically the case with the three main storage dams in the French Alps and their associated powerhouses: Chevril-Malgovert, Roselend-Bathie, and Mont-Cenis-Villarodin. The gravity-based generation profiles of these three complexes, which generate approximately 2500 GWh of electricity per year, would be substantially changed (and possibly decrease) on account of the new approach to water use management. On the other hand, the reversibility created in converting a plant to a pumped storage scheme brings essential added flexibility to the electrical system as well as increased power, largely offsetting these new operating constraints.

As regards costs, pumped-storage hydropower is currently the most economical means of storing energy on a large scale, as RTE[28] states in its economic analysis of flexibility sources, and over long periods, with a cost per storable kWh of about €10. This situation is not expected to change fundamentally between now and 2050, or even beyond. As hydraulic structures are extremely durable (with a lifetime of several centuries), and the majority of costs are incurred during the initial civil works, investing in this sector today is not likely to pose an opportunity risk. In other words, it is extremely unlikely that another storage technology will emerge that is capable of competing with pumped-storage plants that have already been fully depreciated. Once built, these facilities will still play a highly valuable role within a fully low-carbon electrical system.

Lastly, the services rendered for both France and its European neighbours are inestimable.

Investing in a large-scale PSP programme gives additional room to manoeuvre if the choice is made to move towards an electricity mix with a large proportion of VRE, by reducing or even eliminating the need to resort to grid-forming technologies which are yet to be commercially demonstrated and could lead to stability issues.

Since pumped-storage hydropower is based on high-capacity synchronous turbine-generator units, it provides all the system services required by the grid (primary, secondary and tertiary reserves, voltage regulation, reactive power, interruptible load, black start), as well as a high level of inertia. And inertia is something severely lacking in VRE such as wind and solar power. Pumped-storage plants can deliver this inertia by conventional means during pump and turbine operation, or else be used as synchronous condensers when the turbine-generator units are not operating, by their very essence doing away with part of the need for dedicated synchronous condensers to stabilise a grid that is heavily dependent on VRE.

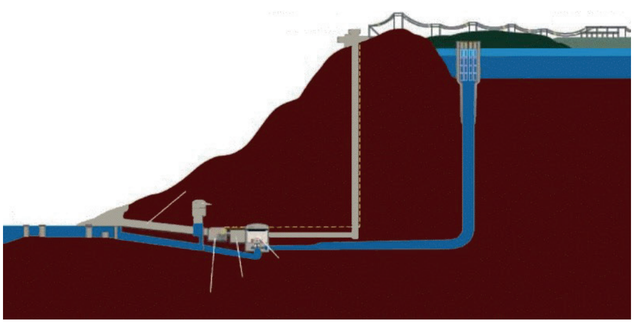


Fig.22 - Cross-section illustration of a pumped-storage facility

Ultimately, although the choice has been made in this scenario not to consider interconnections as design-critical elements of the electrical system under normal operating conditions, recourse to interconnections is not ruled out in case of unexpected "beyond-design-basis" events. Should conditions arise involving a widespread gross power generation shortfall in France (such as very low winter wind power output combined with a seri-

28 RTE, "Energy Futures 2050" study (in French), Chapter 11 "Economic Analysis", p.557 p.563

ous unpredictable technical incident affecting several nuclear reactors at the same time, as was observed in the winter of 2021-2022), having a large high-efficiency hydro storage component provides a means of dissociating electricity imports from the period when this electricity is actually consumed, thus bringing additional resilience to the European electricity grid while lowering the cost of imports.

For all these reasons, we consider the development of pumped-storage hydropower a "no-regrets" move in which France should invest heavily in light of the exceptional benefits it would bring.

STAKES

RESTARTING A HYDRO PROGRAMME

Energy efficiency:

- low-tech technology requiring few critical materials,
- limited land footprint.

Feasibility and, in comparison with other production and storage facilities:

- a proven, reliable, coherent means of storing energy within a system incorporating a large proportion of VRE.

Integration in the electrical system and services rendered for the grid:

- an additional capacity of 42 GW from new PSPs representing a total reversible capacity of 8 TWh i.e. a quarter of the potential topographically suitable areas identified,
- synergy with the nuclear fleet:
  - eliminates the need for the nuclear fleet to perform rapid load following operations,
  - geographical locations consistent with the cooling needs of riverside nuclear power plants,
- network stabilising service, inertia, reactive power compensation, black start[29].

Other benefits:

- very low cost per kWh of storable energy,
- dispenses with the need for excessively large wind, solar and nuclear fleets,
- services for climate change adaptation: water resource management, flood control and agriculture in addition to the energy dimension,
- kick-starts and ensures the long-term future of a sector of excellence - the construction of hydropower infrastructure - and safeguards the related know-how.

29 A "black-start" is the process of restarting an electric system following a blackout. This requires a power plant capable of restarting without an external power source. Hydroelectric plants usually perform this role.

Other forms of hydroelectric power

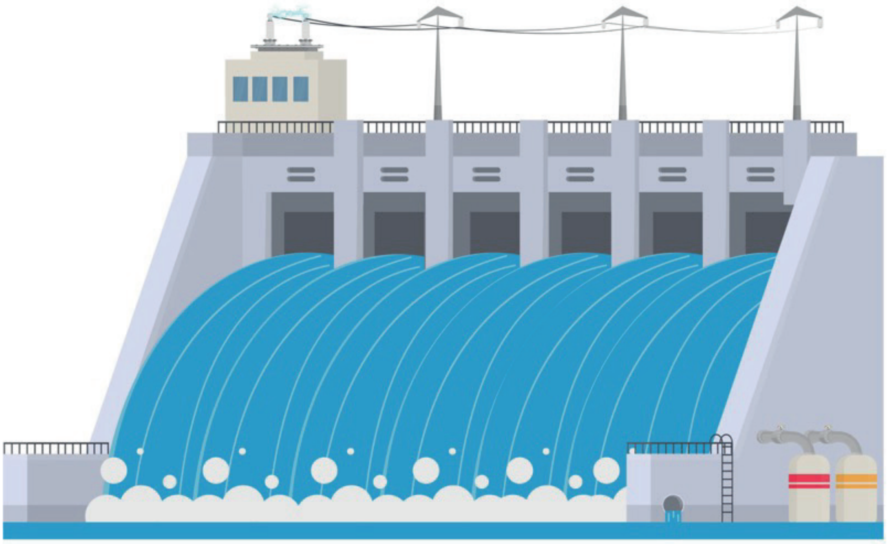


Fig.23 - A run-of-river dam, without a reservoir and hence vulnerable to weather, climate and other uncertainties which affect the flow rate of the river supplying it

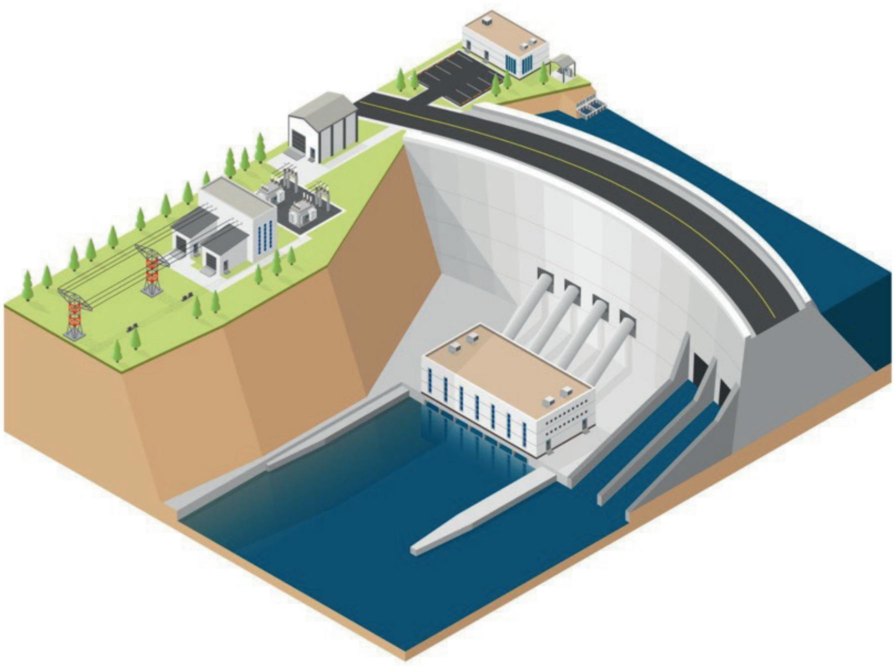
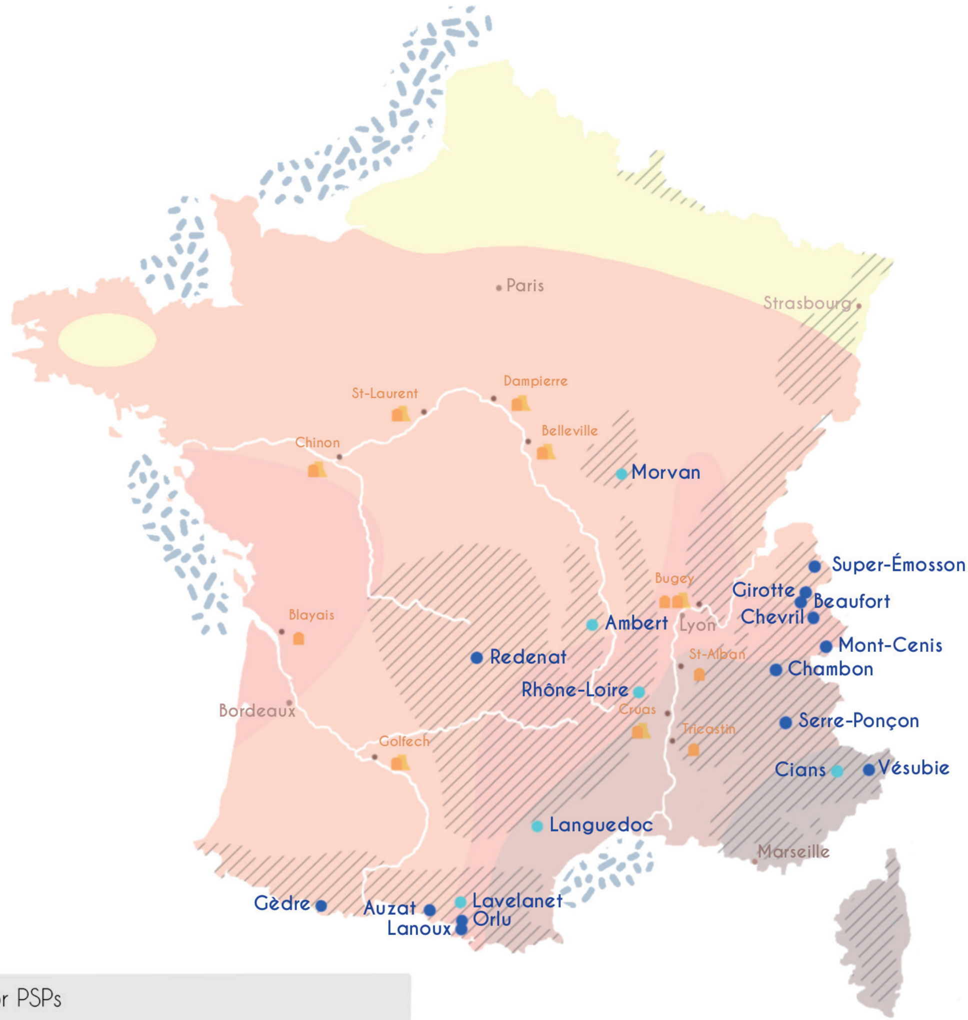


Fig.24 -. A hydroelectric dam with a storage reservoir (also referred to as an artificial lake). PSPs have a storage capacity, unlike conventional hydroelectric dams. The water source is not exclusively natural, however, since it is pumped upstream.

PSPs and associated power generation facilities

PSPs are located as close as possible to solar and wind resources, subject to the applicable topographical constraints. They can also contribute to cooling management for certain nuclear reactors located further downstream.



Suggested sites for PSPs
- New installations
- Using an existing hydropower installation

Nuclear sites on the banks of a river down stream of a PSP
- Existing nuclear reactor in closed circuit
- Existing nuclear reactor in open circuit

Main areas with high offshore wind potential

Main mountain ranges

High potential sites for solar
- <1200
- 1221 à 1350
- 1351 à 1490
- 1491 à 1760
- > 1760

Fig. 25 - Map of a possible strategy for locations of future PSPs, optimised in terms of population displacement, environmental impacts and services to the power grid. This is not an exhaustive map, and other locations may be envisaged in addition to or instead of the sites proposed here.

Installed hydropower capacities

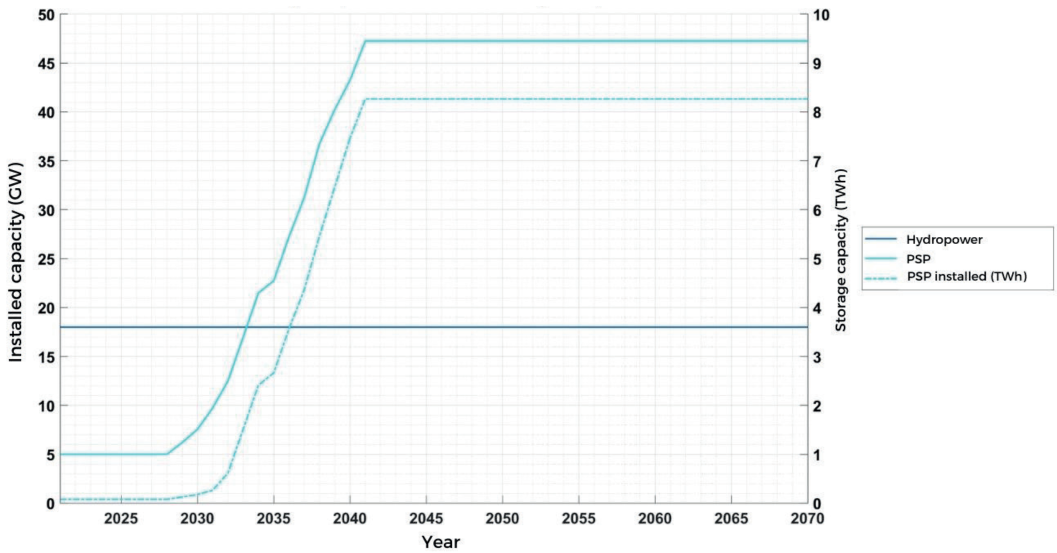


Fig. 26 - Changes to the hydropower and PSP fleet over the scenario pathway. Conventional hydropower remains relatively unchanged. The installed capacity of PSPs increases from 5 to 47 GW, and their generation capacity from 80 to nearly 8200

4. Wind and solar

An essential contribution to a low-carbon electricity supply in the 2030s.

A key, legitimate role

All energy sources and the technologies arising from them have a role to play that depends on the targets set and the context of their use. They are technical tools and instruments at our disposal. They must remain tools we can use to meet our objectives.

Given the configuration of the public debate at the time this scenario is published, it is useful to recall that the objective of the Voices has never been, and will not be, to reject the contribution that VRE must make to the vital effort to achieve global decarbonisation, nor to prioritise the use of nuclear power under all circumstances for dogmatic reasons.

The Voices are not opposed to the development of wind and solar if it is done in a coherent manner and in line with the objectives.

We consider nuclear energy to be the most suitable source for France, and probably all other countries that are not able to rely to a large extent on hydro or geothermal sources, to use as the mainstay of its electricity supply. However, we are perfectly aware that VRE are essential in the context of the race against the climate clock. The aim is to provide, in the short and medium term, an increase in low-carbon electricity generation to support the electrification of end uses, especially use of electric vehicles

Since a significant increase in nuclear power generation cannot take place until after 2040, VRE will be essential in all scenarios.
On the basis of these findings, the association is in favour of accelerating the development of solar and wind. However, for decarbonisation reasons as well as economic, social and strategic considerations, it would be beneficial to relocate their manufacturing chains to France or Europe.

An essential and substantial effort

In our scenario, by 2050 a minimum of 55 GW of solar PV and 60 GW of wind power (including 35 GW onshore and 22.5 GW offshore) will have been deployed, mainly during the 2020s and 2030s, at an average installation rate 2.5 times faster than in 2019.

Wind power generates approximately 130 TWh/year and solar generates 55 TWh/year depending on the annual requirements and export possibilities.
However, with a view to optimising the entire system, the position of these intermittent energy sources in the operation of the French energy mix will have to change.

A role meant to evolve

VRE will no longer take priority over nuclear on the electricity network. Traditionally, the merit order of electricity generation facilities on the grid is determined by increasing value of use (unavoidable energy sources / nuclear-gas co-generation / coal, hydraulic, fuel oil). Nuclear power, the marginal cost of which is usually between €5/ and €15/MWh, is positioned after wind and solar in the merit order. However, in reality management of a power grid cannot be summarised as a single variable cost. Although power modulation has become a speciality of the French nuclear fleet, it is nevertheless more demanding for the equipment, requires heavier maintenance, and imposes stricter safety rules. In addition, it does not necessarily result in more economical use of nuclear fuel, which is supposed to be indicated by the marginal cost.

Indeed, if a unit has not consumed its fuel at the expected rate, either:

- its outage for maintenance and reloading must be rescheduled, disrupting the operator's overall maintenance schedule, which must be adhered to in order to guarantee maximum availability during periods of high consumption in the winter,
- or the unconsumed fuel is lost and must be sent as-is for reprocessing.

Thus, modulation increases maintenance costs while not significantly reducing fuel costs.
For these reasons, the scenario's "merit-order" has been modified so that renewable energy sources, which are theoretically much easier to modulate downwards, no longer take priority over nuclear energy. In practice, nuclear energy would keep pace with average daily consumption irrespective of RES generation, with daily load following implemented initially via exports and peak shaving and then by PSPs as and when these are commissioned.

Deployment of VRE

Given the planned deployment rates and the predicted increase in consumption, the contribution from renewables (including hydropower) could reach between 35 and 40% by 2040, before decreasing slowly over the 2040s as the nuclear fleet is ramped up to provide for about 30% of generation by 2050.

Operators will be encourage to install new capacities as close as possible to the specific pumped storage facilities that they are intended to feed into.

Beyond 2050, it will be equally possible to conserve this same level in the mix so as to begin reducing generation from renewables as and when wind and solar facilities reach the end of their working life. This decision will depend on the economic conditions at the time, as well as on a democratic choice of energy policy.
A gradual decrease in VRE in France beyond 2050 is thought to be desirable with regard to the natural resources consumed, so they can be reserved for regions of the world that may still be having difficulty phasing out fossil fuels. Wind and solar would hence be transition energies in the move towards a long-term low-carbon mix, and would then assume a supporting role.

Installed wind/solar capacities

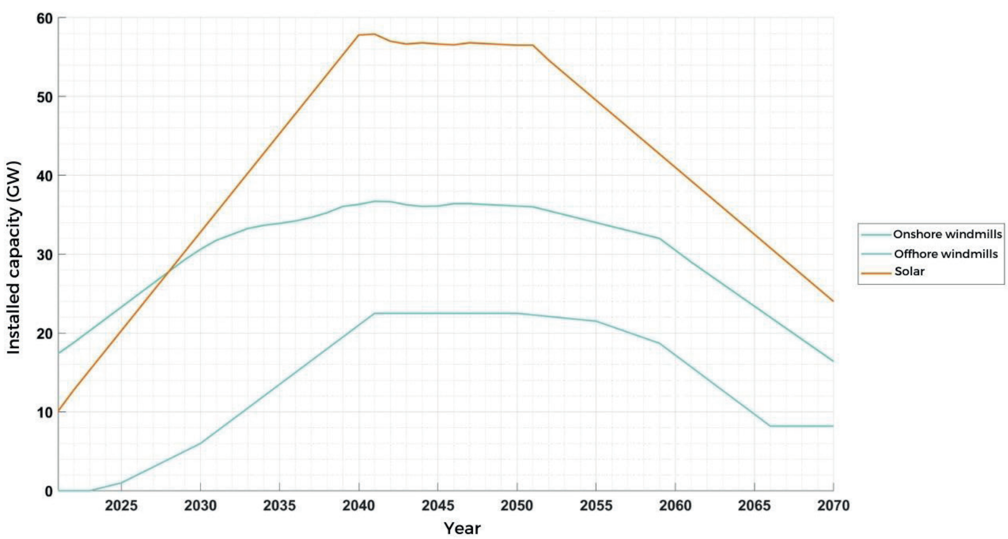


Fig. 27 - Changes in installed wind and solar capacities. No capacity decreases prior to 2050 (insofar as decarbonisation has not been achieved). The sharp increase in these VRE observed up until 2040 can be continued if problems are encountered with extending the lifetime of the original nuclear fleet beyond 60 years.

Deployment of wind

Location tends to determine the distribution of installed capacities across different regions, encouraging a much greater deployment in the southern half of France in order to bring wind power generation closer to the electricity storage facilities (PSPs) in the Western Pyrenees,

the south of the Massif Central and the Alps.

In this case, a trade-off may be made depending on future technological developments. If floating wind power proves an economic failure, regrouping onshore wind farms in the south of the country would compensate for the under-exploitation of the offshore potential of the Mediterranean Sea, which is entirely dependent on the capacities of the floating wind sector, whilst reserving fixed offshore wind power for northern France. Conversely, successful industrialisation of floating wind technology would reduce the requirement for onshore facilities in the south of France, and such facilities could then be redistributed across the rest of the country. Close attention should therefore be paid to the development of floating wind power, since it could have a key influence on the geographical distribution of wind power generation in France. The objective would hence be to generate 35 GW from onshore wind and 25 GW from offshore wind in 2040, within a total annual production capacity of approximately 165 TWh.

Deployment of solar PV

The deployment of solar should mainly be correlated with changes in the summer-time consumption of air conditioners.
If the latter turns out to be much higher than expected, more solar facilities will be installed. A minimum of 55 GW will be deployed, with a production capacity of at least 70 TWh per year.

Extensive pooling of resources with pumped-storage plants is also planned here, with the installation of floating solar plants on PSP reservoirs wherever possible, creating an estimated generation capacity of 2.5 GW.

Although these deployment rates are clearly faster than the average over the last 10 years in France, they are nevertheless realistic and reasonable, and are in line with the aims of RTE's energy scenarios N01 to N03.

5. Biomass combustion turbines

Meeting peak demand without gambling on hydrogen

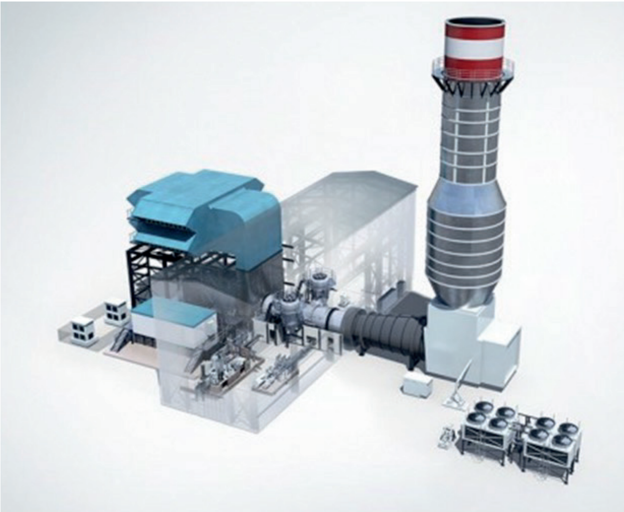


Fig. 28 - Illustration of a gas turbine plant (AE-94.2 model)

The need for flexible generation during ultra-peak hours, with very low fixed costs and high marginal costs, has inspired consideration of the various ways to eliminate - or at least greatly reduce - the greenhouse gas emissions associated with this type of generation, which usually involves low-efficiency fuel oil or gas. These constraints have been decisive factors in choosing to use combustion turbines. New facilities of this type with a total capacity of 20 GWe will be commissioned between 2027 and 2034.

They usually require fuel in either liquid or gaseous form. Since the scenario has opted to avoid technological gambles relating to hydrogen, the default fuels for combustion turbines could be biodiesel and bioethanol, which are easy to obtain and store (substituting electricity for fossil fuels in road vehicles will free up several TWh per year, which will instead be used to fill the strategic reserve). However, since agrifuels and biogas must be reserved first and foremost for the last non-electricity uses in heavy-duty transport (shipping and aviation, agricultural and construction site vehicles, etc.), the scenario proposes a more exotic fuel for this type of use: wood.

It is not widely known that gas turbines are capable of operating with solid fuels under certain conditions.

Experimentation with this type of fuel actually dates back quite a long way, with the first tests using pulverised coal taking place in 1940[30] for locomotives, although they were inconclusive due to erosion of the blades by combustion residues and to the availability of diesel. Full-scale experiments using sawdust in modified aviation turbines in the 1980s confirmed that the concept was viable[31], but it was not developed further due to the low price of hydrocarbons and lack of concern for the climate at the time.

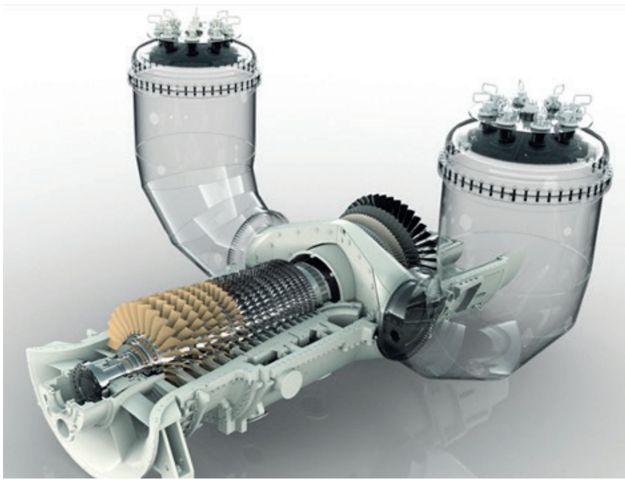


Fig. 29 - Illustration of a combustion turbine (AE-94.2 model) which is potentially suitable for adaptation to biomass due to its two offset combustion chambers

30 M. C. DUFFY (1993) The Coal-burning Locomotive Gas-Turbine Project, Transactions of the Newcomen Society, 65:1, 75-93
31 Hamrick, J T. Development of biomass as an alternative fuel for gas turbines. United States: N. p., 1991. Web. doi:10.2172/5685622.

The operating principle is exactly the same as that of any other gas turbine, but here the fuel is in the form of a powdery solid (sawdust).
The advantage of wood is that it is abundant, can be easily stored in silos in quantities of hundreds of thousands of tonnes (in the form of compacted sawdust pellets), and can be obtained from a very wide range of solid biomass sources (sawmill residues, trees felled to clear land, used furniture, dedicated miscanthus farming).
In contrast to hydrogen, for which the value chain remains to be created almost in its entirety, mature and efficient logistics are already in place for wood.

This use is not designed to boost demand for biomass, but as a mean of converting unavoidable electricity generation from wood-burning energy to a modular and flexible generation that would add great value to the electricity system.

Indeed, since one of the scenario's objectives is to reduce, or at least not to increase, the overall consumption of biomass, the primary source of material for this sector would be unavoidable waste.
This unavoidable electricity generation from wood currently represents 2.7 TWh/year in an almost constant range around 300 MWe, i.e. between 1.5 and 2 million tonnes of fuel annually. Although this biomass is often used in co-generation, using it in baseload is illogical given how easy it is to store, because it does not contribute to making the electrical system more flexible.

Conversely, stored in reserve and used as a fuel during peak periods, this biomass would for example serve as a back-up, providing 5 GWe for 20 days.

In addition, since a gas turbine is by design a highly versatile machine, it would retain its capacity to burn gas or fuel oil (of fossil origin or not), or even other more exotic fuels (such as used fryer oil) if necessary. In a worst-case scenario, should the constraints on sawdust combustion turn out to be too restrictive, it would be possible to fall back on agrifuels or biogas from anaerobic digestion (and simultaneously re-use existing gas/fuel oil power plants).

This use configuration will contribute to ensuring

Biomass combustion turbine installed capacities

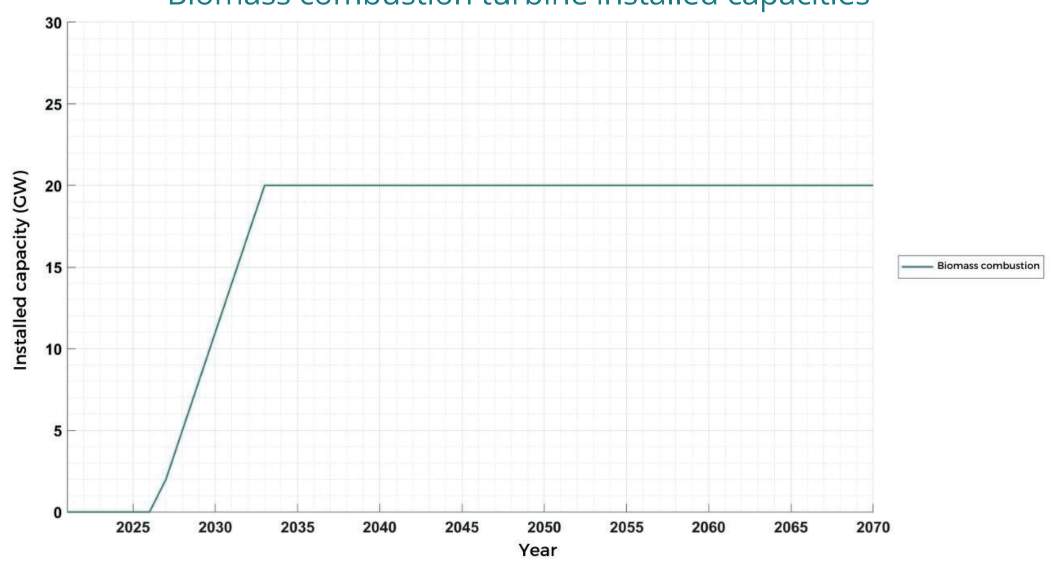


Fig. 30 - Changes in biomass combustion turbine capacities. Their purpose is to replace the last fuel oil and gas combustion
Possibly also in co-generation, to support winter peak shaving by temporarily switching a heat network from a heat pump to this unavoidable heat, whilst supplying additional electricity to the rest of the network.

this option is a "no-regrets" development choice, since it very substantially increases the resilience of the future electricity system, whether it is based mainly on VRE or on nuclear energy.
It should be emphasised that the scenario does not consider any new units until 2027.

Indeed, there are no turbines of this type available on the market today, and a development phase of a few years is needed to adapt a business model to solid biomass.

Although the concept has been proven and validated, it is not without faults. Although ash from wood combustion does not cause abrasion of the turbine blades, unlike powdered coal, the problem of blade clogging remains. In the early days, these turbines would probably not be capable of operating for more than a week at a time before needing to be cleaned. This is not a prohibitive constraint given that these turbines would not be required to operate for more than a few hundred hours per year, but it is significant and must be emphasised.

These facilities will mainly be built in locations in the northern half of the country, to balance out the installation of PSPs in the southern half, and wherever possible on the sites of existing or disused thermal power plants.

This configuration enables the connection to the transmission network and certain flue gas decontamination facilities to be reused. It is also an opportunity to conserve existing local jobs (a key issue particularly relevant to the Cordemais site), and make use of direct rail access for the supply of fuel.

This would be stored in large silos to guarantee each site a minimum self-sufficiency of a week at full power, representing 100,000 tonnes of pellets per GWe of installed capacity. These silos can be constructed on the basis of the model used to equip the British Drax power plant, a 4 GWe coal-fired plant converted to biomass which has four pellet storage domes each containing 88,000 tonnes (diameter 63m, height 50m), comprising a total stock equivalent to 700 GWh of electricity.

Although progress can certainly be made regarding combustion quality or turbine blade protection, this is only because in modern turbines these blades are actively cooled with a film of "cold" gas that protects them at least partly from deposits

IV Comparison of the France 2050 energy scenarios

The prospect of France's Multi-Annual Energy Plan being updated in 2023 prompted the publication of a large number of prospective scenarios setting out energy mixes for the country up to the year 2050. Among these, the in-depth work carried out by RTE in response to a request from the government produced six scenarios, including the N03 selected by the government to serve as a baseline for national energy planning processes.

While all the scenarios propose visions and approaches that can usefully be considered, Voices of Nuclear wished to explore hypotheses imposing a degree of realism and simplicity, and even thrift, that we felt they lacked. Our aim is to define a path that is as reliable, resilient and robust as possible toward achieving the goals of decarbonising the economy, preserving the environment, and ensuring a sufficient supply of electricity. The Voices scenario sets itself apart through its desire to minimise vulnerability to technological, industrial, geopolitical and social uncertainties. A comparison with the other prospective scenarios shows that it succeeds in reaching its objectives at least as well as its alternatives, while achieving a higher degree of feasibility and reliability.

1. Achievement of objectives

	Human	Climat	Environment*	
2050	Electricity Consumption (TWh/year)	Carbon intensity (gCO2eq/kWh)	Land use (kha)	Land use (ha/TWh/yr)
French mix 2019	474	36	-	-
Voices	**792**	**11.0**	**990**	**1 250**
RTE N03	645	10.8	1 086	1 684
RTE N1	645	13.2	1 346	2 087
ADEME S3	605	13.3	1 379	2 279
Négawatt 2022	550	14.6	1 419	2 579
Négatep	845	17.7	682	807
CEREME	836	23.7	503	602

* this category should be completed with additional indicators relating to human factors (accessibility of electricity), climate (consideration of other greenhouse gas emissions) and the environment (pollution, waste, loss of greenfield land)

Although they are not the biggest consumers of metals and rare earths, diffuse intermittent renewable energy sources consume much more of such resources than hydropower and nuclear power. A high penetration of intermittent sources also goes hand-in-hand with a greater need for grid infrastructure and - in the absence of PSPs on the requisite scale - battery storage, both of which consume large quantities of **critical metals.** Increasing the use of diffuse sources in the mixes proposed by other energy scenarios would hence be to the detriment of other uses, including freeing natural areas for the benefit of ecosystems and biodiversity.

The assumption adopted in the Voices scenario **is as prudent as possible in regard to dependence on electricity imports.** The Voices consider that making the reliability of France's electricity supply contingent on achievement of the targets set by all the neighbouring countries is a high and uncontrolled risk, both in terms of the probability of it occurring and the severity of the consequences should it fail.

Moreover, the assumptions made by some of the scenarios in this comparison regarding **potential energy efficiency gains** are based on some particularly bold technological and technical gambles. The Voices scenario incorporates these gains as desirable margins and opportunities to boost reliability, rather than as a structural basis that plays a decisive role in achieving the objectives. Most of the scenarios assuming that consumption will be relatively low by 2050 (ADEME or Négawatt, for example) justify this assumption on the basis of advanced and widespread thermal insulation of buildings, significant efficiency gains in industry, and equipment that is, as yet, not completely proven.

As regards energy efficiency and energy savings, while the association hopes that significant progress will be made on this front, the operational success of our scenario does not depend on such progress. If systemic efficiency and energy saving are to become a reality on a large scale, sweeping changes in habits and behaviour are required that must be adopted rapidly and willingly by a large majority of the population. We do not wish to gamble the future of the generations to come on such assumptions.

In addition, scenarios such as ours that incorporate assumptions of a significant increase in electricity consumption are the only ones capable of guaranteeing **re-industrialisation** for our country, while providing the means to electrify whole industrial sectors in the transition to net zero, as well as other everyday life end uses .

Lastly, the Voices of Nuclear scenario is one of the very few forecasts that **does not anticipate the deployment of a large-scale hydrogen network,** on account of its high cost, low efficiency and potential for accidents. The Voices prefer to provide industrial firms with the quantities of electricity they need and allow them to use it to decarbonise their own processes and facilities.

All the technologies and techniques contributing to the Voices scenario are proven and already commercially deployable..

This choice, too, sets the Voices scenario apart from others which involve a larger contribution from intermittent renewable energy sources, and which must rely for a substantial part of the country's energy future on technologies such as storage or grid stabilisation. These technologies are a long way from proving their viability, whether on their own or on an energy system scale.

The incompressible uncertainties in the Voices scenario are human in origin. Uncertainties of this type are inherent to all the other scenarios featuring in the public debate on at least a similar level. These are **uncertainties associated with decisions that must be made** and that have major implications in terms of public policies: a finite time frame / public acceptability of new infrastructure projects / development of the requisite skills and availability of human resources / constraints imposed on consumption habits and uses.

2. Assumptions underpinning the scenarios

Replacing global consumption of fossil energy, which currently accounts for 80% of the total, along with a substantial share of biomass consumption - another 10% - with low-carbon energy sources, which currently represent less than 10% of the total, is a huge challenge. It is only slightly less so for France, where two-thirds of the final energy consumed still come from fossil sources.

It is made even greater by the fact that these low-carbon energy sources are not as easy to use as fossil fuels, which are accessible, high-density, versatile, and easy to implement, store and convey. These properties have made them, and still make them, the energy sources of choice for humanity, even taking into account their finite nature and the negative consequences they have for the climate, the environment and health.

The challenge becomes greater still when one considers that they must be replaced within an extremely short period of time, currently estimated at less than 30 years.

We cannot avoid this challenge, and we have no choice but to meet it.

To achieve this, we must make plans based on assumptions falling within three types:

- the **technological and industrial** dimension: do we have the technologies we need to achieve the objectives, depending on the available resources we choose to adopt?
- the environmental and natural dimension:
  do we have the space, mineral resources, non-mineral resources and water resources to support our plans?

• the human dimension:
will we accept the changes that have to be made, and succeed collectively in making them?

With a view to maximising the chances of fulfilling the promises made to the future generations, the Voices have sought to identify, in scenarios available to the public, the main assumptions and risks, explicit or implicit, on which the success of these scenarios depends.

Each of the scenarios examined contains major assumptions, , which can also be referred to as bets or gambles. These assumptions increase the uncertainty associated with realization of the announced programs and lower the probability of achieving achieving the objective of a carbon-neutral French - as well as European and global - energy system by 2050.
The table below proposes a qualitative assessment of assumptions included in the various energy scenarios we consider at least partially if not completely unavoidable, and which we sought to minimise as a common thread running throughout our scenario.

The one risk common to all the scenarios - including that of the Voices, which we have also striven to minimise - remains the human factor.

The positive message conveyed by the Voices scenario is that we are in a position to solve the difficult equation of making France carbon-neutral by 2050 without having to take risks related to anything other than the human factor. And mastering those risks depends solely on us.

Assumptions over ...							
All scenarios, **including that of the Voices** make assumptions over : • The fact that decisions are taken early enough • Acceptance of new infrastructures • Human resources and skills required							
RTE N03	The scale of SMR development	The availability of electricity import	The deployment of a hydrogen network				
RTE N1	The scale of network flexibility	The availability of electricity import	The deployment of a hydrogen network	Feasibility of an electricity network with high VRE integration	Development of battery storage	Land availability	
ADEME S3	Profound changes in behaviours and network flexibility	The reality of biomass capacities	The deployment of a hydrogen network	Availability of rare metals and materials	Hypothesis on energy-efficiency gains (buildings...)	Land availability	Sufficient electricity production to sustain reindustrialisation
Négawatt 2022	Profound changes in behaviours and network flexibility	The reality of biomass capacities	The deployment of a hydrogen network	Availability of rare metals and materials	Hypothesis on energy-efficiency gains (buildings...)	Land availability	Sufficient electricity production to sustain reindustrialisation
Négatep	The immediate construction capacity of the nuclear industry		Energy mix not decarbonised in 2050	Still a high carbon-intensity energy mix in 2050			
CEREME	The immediate construction capacity of the nuclear industry	Consequences of maintaining fossil production	The deployment of a hydrogen network	Still a high carbon-intensity energy mix in 2050			

3. Power generation facilities deployed

	Nuclear (GW/TWh)	Onshore wind (GW/TWh)	Offshore wind (GW/TWh)	Solar (GW/TWh)	Hydropower (GW/TWh)	PSP (GW/GWh*)	Biomass (GW/TWh)	Gas (GW/TWh)
French Mix 2019	63 / 380	16 / 34	0 / 0	10 / 12	22 / 60,0	5/80	1 / 5	19 / 43
Voices	**89.7 / 560**	**35 / 66**	**22.5 / 66**	**55 / 54**	**22 / 63**	**42 / 8400**	**20 / -****	**0 / 0**
RTE N03	51 / 328	43 / 91	22 / 74	70 / 86	22 / 63	8/128	2 / 12	0 / 0.5
RTE N1	29 /165	58 / 124	45 / 153	118 / 144	22 / 63	8/128	2 / 12	0 / 0.5
ADEME S3	22 / 132	58 / 108	44 / 132	142 / 178	22 / 64	8/128	8 / 8	8 / 15
Négawatt 2022	0 / 0	61 / 153	38 / 152	144 / 168	22 / 54	5/80	5 / 5	0 / 0
Négatep	100 / 688	18 / 45	0 / 0	10 / 11	22 / 70	5/80	3 / 11	20 / 20
CEREME	100 / 668	0 / 0	0 / 0	49.6 / 54	22 / 69	5/80	2.5 / 2.5	20.1 / 33

In pale blue, the lowest TWh value per generation source, and in dark blue the highest value (excluding current mix) for each column evaluated
* Not used in a normal year

The Voices scenario corresponds neither to the energy mix containing the largest share of nuclear power nor to the one most favourable to rolling out VRE. It sets itself apart through its premise of gradually abandoning gas networks, whether fossil, hydrogen or biomass, and of harnessing France's hydroelectric potential.

The ratio adopted for the breakdown between offshore and onshore wind is similar to that used in RTE's N03 scenario. The Voices scenario is more cautious regarding the development of solar photovoltaic, however, and focuses on its qualitative aspects.

The share of hydropower generated by hydroelectric dams is similar in all the scenarios, but the Voices scenario stands out with its heavy reliance on pumped-storage hydropower, the potential of which is currently far from being harnessed to the full. As regards biomass, whereas the other scenarios call on this energy source in normal operating conditions, the installed capacities included in the Voices scenario are used only to cover occasional needs during ultra-peak hours.

The assumptions in the Voices scenario place the focus and priority on phasing out fossil fuels, including all gas use, unlike most of the other scenarios. Along with RTE's N03 scenario, it is also the most advantageous as regards the carbon intensity of the electricity mix.

The consumption variations adopted are at the upper end of the range and comparable to those of RTE's so-called re-industrialisation variant, and to those of neighbouring European countries.

Comparison of assumptions for electricity consumption increases in neighbouring European countries

	The Voices	France (RTE)	Germany	Italy	Spain	UK	Netherlands
Official projection of percentage increase in electricity consumption in comparison with 2019	**+65%**	+25-40%	+30-80%	+45-55%	+30%	+80-125%	+75-120%

Given its heavy reliance on nuclear power, which is particularly dense in terms of power per area occupied, the 2050 mix proposed by the Voices makes very sparing use of land area. The only scenarios that do better on this criteria anticipate a rapid increase in electricity consumption without a substantial deployment of VRE, a combination which currently appears to be out of reach.

Therefore, in spite of an ambitious PSP development plan, the land footprint of the mix proposed by the Voices scenario is significantly smaller than that of scenarios with a large share of biomass and solar photovoltaics.

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