



Energy Pathways to 2050

Key results

October 2021

EXECUTIVE SUMMARY

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ENERGY PATHWAYS TO 2050

WHY, WHEN, HOW?

In compliance with its legal obligations (Generation Adequacy Report) and at the request of the French government, in 2019, RTE launched a wide-ranging study on the evolution of the power system called "*Energy Pathways 2050*."

This project was undertaken at a crucial point in the public debate about energy and the climate, a debate that is shaping the strategies that will be adopted to move away from fossil fuels and achieve carbon neutrality in 2050, per the Paris Agreement goals. The process will involve a deep transformation of the economy and radical changes in the transport, industrial and building sectors, which to this day remain very dependent on oil, fossil gas, and even coal in some cases.

All the science makes clear that urgent action is vital. The IPCC report published in August 2021 offered yet another reminder of the need to reduce greenhouse gas emissions very quickly to limit the potentially catastrophic effects of climate change. The next COP, to be held in Glasgow in November 2021, is expected to acknowledge this reality and lead to the adoption of new targets for the coming decade.

The transformation required to transition away from fossil fuels must be completed within the next three decades and accelerate sharply between now and 2030.

Some might consider France's contribution to meeting these climate goals meaningless or negligible, given its share of global emissions (about 1%). However, the country's per capita emissions remain above the world average, especially when the impact of imports is taken into account (carbon footprint). Moreover, the technological and industrial solutions that will be necessary to meet climate goals are likely to give France and countries in Europe a substantial competitive edge on the world stage.

The energy crisis of late 2021 shows that phasing out fossil fuels is not only imperative for the climate: it is also a reminder that Europe's heavy reliance on hydrocarbon-producing countries can come at an economic cost, and that

having access to low-carbon generation sources domestically is also a question of independence.

A variety of options are available. They have some points in common (decrease in energy consumption, increase in the share of electricity in the mix, reliance on renewable energy sources) but also major differences – in terms of how quickly consumption will evolve and how it will be broken down by end-use, the development of industry, the future of nuclear, the role of hydrogen, etc. RTE's *Energy Pathways to 2050* report addresses the need to document these options by describing the technical changes that will need to be made to the system and the related costs, the environmental consequences in a general sense, and by explaining the implications these changes will have for lifestyles.

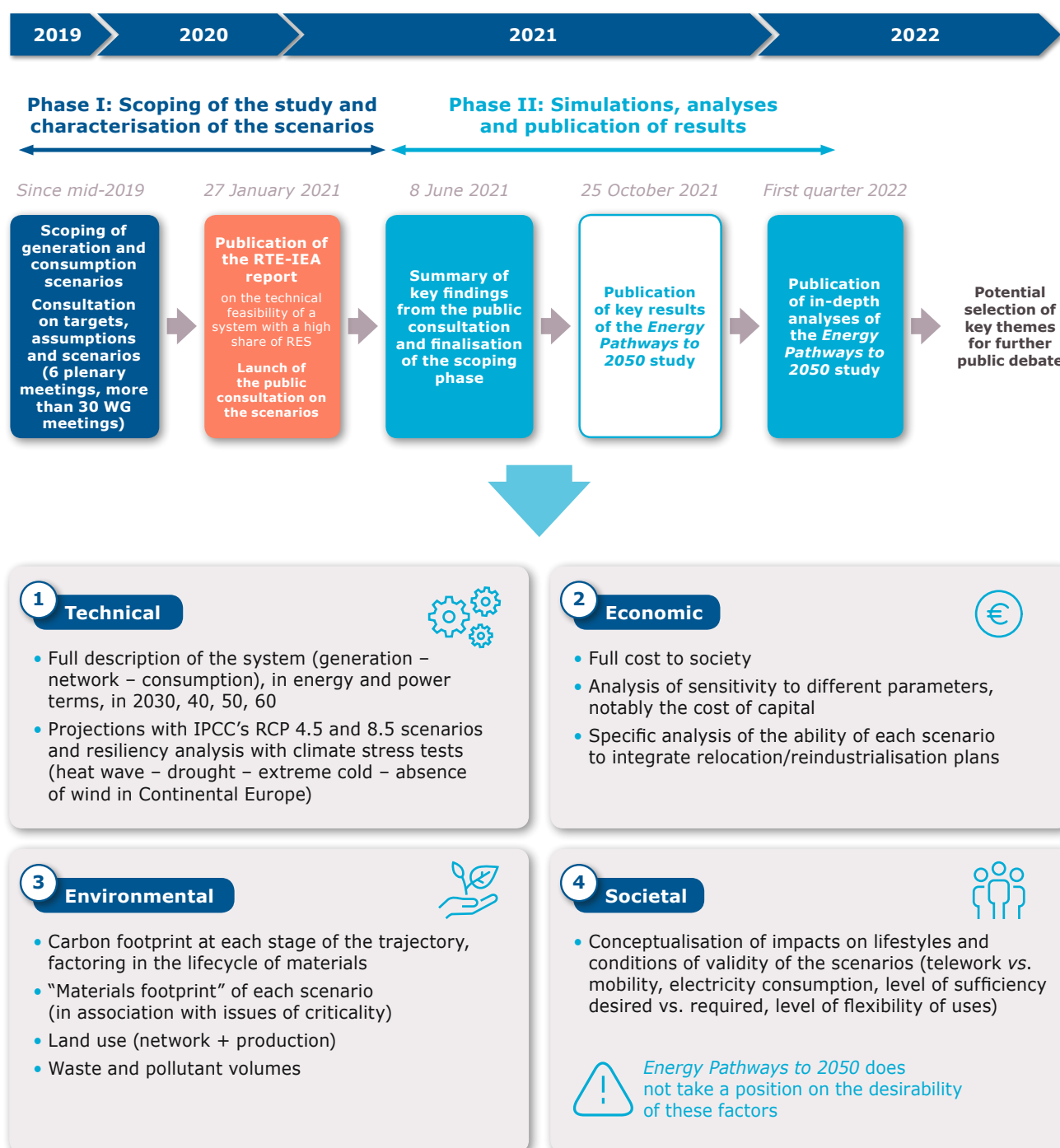
Preparing the report began with far-reaching technical work, relying on significant simulation and computing efforts to characterise in a rigorous manner a wide variety of power systems that would enable carbon neutrality to be achieved in 2050.

It also involved unprecedented effort in terms of consultation: the different scenarios were prepared out in the open, all study parameters were discussed, tracked and debated in working groups and during a plenary session with all consultation participants, applying an open and transparent method that allowed each interested party to express its views and be heard. The study timetable notably evolved to take into account all comments received and to make the process more robust by integrating numerous scenarios and variants not initially included. All in all, 40 meetings were held, bringing together experts from about 100 different bodies (energy sector firms, NGOs, associations, think tanks and institutes, regulatory and government agencies, etc.). The consultation system was expanded to include a scientific council that will have tracked all work undertaken since the spring of 2021.

Phase I of the study, dedicated to defining targets, methods and assumptions, was completed in the first quarter of 2021. It was the subject of a broad public consultation, one that drew responses from parties well outside the traditional circle of "expert

stakeholders” that usually participate in this type of exercise: nearly 4,000 entities and individuals participated via very detailed specific contributions,

open letters, petitions and online actions. A preliminary report summarising the results of this phase was made public on 8 June 2021.



KEY FINDINGS OF THE ENERGY PATHWAYS TO 2050 REPORT



Main challenge: transition away from fossil fuels

CONSUMPTION



Reducing consumption through energy efficiency, and possibly energy sufficiency, is key to reaching climate targets



Energy consumption will decrease but demand for electricity will increase as it replaces fossil fuels



Accelerating France's reindustrialisation by electrifying processes will increase its electricity consumption but reduce its carbon footprint

TRANSFORMATION OF THE MIX



Carbon neutrality cannot be achieved by 2050 without significant renewable energy development



Without new nuclear reactors, renewable energy will need to be developed at a pace exceeding that seen in the most dynamic European countries

ECONOMY



Building new nuclear reactors makes economic sense, particularly if it allows a 40 GW fleet to be in place in 2050 (existing plus new nuclear plants)



Renewable electricity has become a competitive solution. This is especially true in the case of large solar plants and onshore and offshore wind farms



The system will require very different types of flexibilities to ensure security of supply in the different scenarios. There is an economic case for increasing demand-side management, expanding interconnections and hydropower storage, and installing batteries to support solar power. Additionally, new thermal power plants fuelled by decarbonised gas (including hydrogen) will be necessary if the nuclear revival is minimal. And this need will be massive – and thus very costly – if the system moves toward 100% reliance on renewables



Under all scenarios, the size of the power grid will need to be adapted rapidly to make the energy transition possible

SYSTEM AND TECHNOLOGIES

- 10** The creation of an efficient “low-carbon hydrogen system” will help decarbonise certain sectors that are hard to electrify, and will be necessary for energy storage under scenarios calling for very robust renewable development
- 11** Scenarios with a very high share of renewables in the mix, or the one calling for the lifetime of existing nuclear reactors to be extended beyond 60 years, imply overcoming major technological challenges for carbon neutrality to be reached in 2050
- 12** Starting now, the transformation of the power system must take into account the likely consequences of climate change, particularly its effects on water resources, heat waves and wind patterns

LAND USE AND THE ENVIRONMENT

- 13** Renewable energy development raises concerns about the use of land and the limitation of other uses. Its growth should be able to accelerate without putting excessive pressure on soil artificialisation, though care must be taken to preserve living environments in each region
- 14** Even when factoring in the full carbon footprint of infrastructure over its entire lifecycle, electricity in France will remain largely decarbonised and will make a significant contribution to carbon neutrality by replacing fossil fuel energy
- 15** There may be tension around mineral resource supply in the energy transition economy, particularly for certain metals, and it will be necessary to plan accordingly

GENERAL

- 16** By 2050: it will be possible for France to develop a power system adapted to carbon neutrality while keeping costs under control
- 17** By 2030: developing renewable energy sources as quickly as possible and extending the lifetime of existing nuclear reactors in order to maximise low-carbon generation, will increase the chances of reaching the “-55% net” target set in the new European package
- 18** Whatever the scenario considered, action cannot be delayed



**MAIN CHALLENGE:
TRANSITION AWAY FROM
FOSSIL FUELS**

Achieving carbon neutrality will require transforming the economy and lifestyles, and restructuring the power system in such a way as to allow electricity to replace fossil fuels as the country's leading energy source

1 To uphold its climate commitments, France must move away from the fossil fuel energy on which its current economy and lifestyles are built

Some 60% of the energy used in France is from fossil sources – primarily petroleum products (about 40%), natural gas (about 20%) and coal (less than 1%).

This energy depends on imports from producing countries (particularly Saudi Arabia, Kazakhstan, Russia, Nigeria and Algeria for crude oil and Norway, Russia, the Netherlands and Nigeria for gas). Successive energy crises have shown the degree to which this dependence exposes France to fluctuations in energy product prices on global markets, which are in turn shaped by complex geopolitical dynamics and the state of the world economy.

Yet this same system, built on fossil fuel energy, was the engine of France's economic growth during the "Glorious Thirty" (1945-1975). Even during oil shocks, it ensured that France had access to energy that was affordable, always abundant, and easy to store. Today, fossil fuels cover more than 930 TWh of final consumption a year, compared with 430 TWh for electricity.

Unlike in the majority of neighbouring countries, the power system in France does not run primarily on fossil fuels. The key characteristic of the French

system is that it relies in majority on 56 nuclear reactors, most of which were built and commissioned within a short time of one another between the late 1970s and early 1990s, adding to the country's already considerable hydropower capacity (60 TWh). France launched its nuclear electricity programme with an eye to achieving energy independence following the oil shocks. There is no denying today that the nuclear fleet is a major advantage in France's climate change fight, since it enables the production of large quantities of almost entirely decarbonised electricity.

As in all Western democracies, France's use of civil nuclear power has sparked democratic debate. Discussions have in recent years focused so much on the share of nuclear in the electricity mix that some might have believed it was nuclear's share of total energy consumption in France that was being debated. **But the fact is that while nuclear does account for 70% of the electricity produced in France, it represents less than 20% of final energy used in the country.** The dominant share of nuclear in French electricity production should not overshadow the country's reliance on fossil fuels to meet its energy needs. As a result, achieving carbon neutrality will require phasing out nearly all of this fossil fuel energy.

2 France's strategy for the future: low-carbon and independently produced energy, built on a foundation of energy efficiency, low-carbon electricity and the development of biomass uses

France's strategy for achieving carbon neutrality is laid out in its National Low-Carbon Strategy, or NLCS (*Stratégie nationale bas-carbone* – SNBC), which is reviewed every five years. The most recent version of this document, published in 2020, provided the framework for RTE's "Energy Pathways to 2050". The scenarios in it explore a wide range of variants that allow carbon neutrality to be reached in 2050.

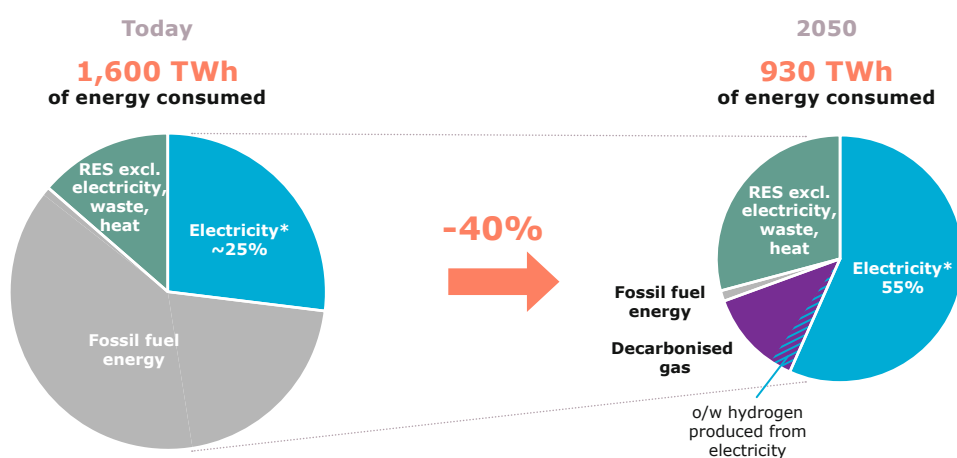
The study is a way to test the application of the principles of the NLCS, to gauge its consequences, and to prepare for the revision of France's energy and climate strategy in 2023, when a new programme law will be introduced.

On the *demand* side, the NLCS relies first and foremost on energy efficiency: it calls for final energy consumption in France to be reduced by 40% within 30 years. This is a very ambitious target, one that is at the high end of the range of strategies in neighbouring countries, and would require energy consumption in France to fall back to the same level as in the late 1960s.

On the *supply* side, the NLCS rests on two pillars: decarbonised electricity and domestically produced biomass. It thus excludes massive imports of green gases, of non-sustainable biomass and of decarbonised fuels, contrary to what is being planned in other European countries. In other words, France made the decision in 2020 to move toward a system that is carbon neutral and sovereign. The implications are very far-reaching.

On the one hand, the NLCS implies a massive effort to develop biomass, the energy that will see the biggest gains under the French strategy. On the other, the NLCS calls for a rise in electricity consumption, though in most cases the increase is smaller than what is planned in neighbouring countries like Germany, the United Kingdom and Italy. These comparison points must be taken into account in *Energy Pathways to 2050*, knowing that the most recent carbon neutrality scenarios all call for higher electrification targets than those set just a few years ago. In *Energy Pathways to 2050*, the framework assumptions of the NLCS are preserved with a slight increase for electricity consumption.

Figure 2 Final energy consumption in France and under the NLCS



* Final electricity consumption (excluding losses, excluding consumption related to the energy sector and excl. consumption for hydrogen production)
Total electricity consumption in RTE's baseline trajectory = 645 TWh

3 A factor often overlooked in the French debate: the foreseeable closure of second-generation nuclear plants over the coming decades

One resource France can count on to meet 645 TWh of electricity demand in 2050 is its decarbonised generation capacity, which already stands at around 500 TWh. This makes the “hurdle” it must overcome that much lower than in other countries (existing low-carbon production is close to 300 TWh in Germany, 200 TWh in the United Kingdom and 100 TWh in Italy, and each of these countries is planning for electricity consumption to approach 600-800 TWh 30 years from now).

Yet it is impossible to grasp the magnitude of the challenge France faces based solely on this static vision: the average age of its nuclear power plants is 36 years, and the reactors built in the late 1970s and early 1980s are gradually reaching the planned lifespan of 40 years that was factored in when they were designed. While the lifetime of these reactors is being extended based on recommendations from and under the aegis of the country’s Nuclear Safety Authority, ASN, it is generally agreed that it will probably not be possible to keep the reactors in service beyond 60 years, except in exceptional circumstances and subject to specific safety measures being undertaken.

It is therefore essential to craft an industrial strategy that factors in the foreseeable closure of France’s historical nuclear power fleet, which today makes a huge contribution to keeping the country’s greenhouse gas emissions low and keeping domestically produced electricity competitive. Final closures will be very close together in time (“cliff effect”), given the exceptional speed with which France built up its nuclear fleet in the 1980s.

Media coverage of the energy debate in France sometimes fails to consider these closures, acting as if the current electricity mix could be maintained over the long term. Serious long-term energy forecasts cannot afford to overlook such a central

element, and it must be taken into account in France’s energy and climate strategy.

Against this backdrop, two key timeframes can be identified.

In the short/medium term (2030-2035), any decisions about shutting down nuclear reactors would be political. Only two options exist for increasing the country’s decarbonised electricity generation potential over this period: keep the nuclear reactors operating (there is not enough time under any scenario to build new ones by then) and develop renewable energy sources. The weighting assigned to each of these solutions is defined in the 2020 Multiyear Energy Plan (*Plan la Programmation pluriannuelle de l’énergie – PPE*), and will be readjusted when that plan is next revised in 2023. **The readjustment must take into account the energy situation that has emerged in recent years:** more binding climate targets for 2030, a more fragile landscape in terms of security of supply due to tensions around hydrocarbon sourcing, rising energy prices, and reduced margins on the European power system.

Over the longer term (2050-2060), the decommissioning of second-generation nuclear reactors will be an industrial constraint: in addition to supporting the projected increase in electricity consumption, France’s electricity generating fleet will need to undergo extensive changes to replace some 380-400 TWh of annual production capacity.

France must make its energy choices over the coming years with this future in mind: it must increase its decarbonised electricity generating capacity, while at the same time planning for the closure of most of the generation plants that currently meet its needs. These choices appear to be as momentous as those made in the wake of the oil shocks of the 1970s.

4 Options on the table for the power system: “renewable + nuclear” or eventually “100% renewable”

The possible courses of action to tackle this challenge are not the same today as after the oil shock. Since fossil fuels are no longer an option; carbon capture and storage (CCS) is not a preferred solution for reasons related to its technical maturity, acceptability and technical availability; and given that France does not wish to rely on massive imports of clean fuels to achieve carbon neutrality, the debate about decarbonised electricity generation is focusing primarily on the potential split between renewable energy and new nuclear reactors.

The terms for comparing the economic attributes of the two energies have evolved. Historical nuclear has been very competitive and remains so today, but the cost of third-generation reactors has increased, while that of renewables has decreased. However, the very characteristics of wind and solar power make it impossible to reach a conclusion based solely on a comparison of production costs: the variability of production must be compensated by flexible resources, and their integration into the system requires grid reinforcement. Discussions must therefore compare the full cost of these different options (“system costs”) rather than just the cost of the technologies individually.

The nature of the societal debate has also changed. While some still oppose nuclear, citing the risk of accident and ethical considerations associated with radioactive waste, renewable energies are also the

subject of controversy in terms of their societal and environmental impacts: impact of hydropower on biodiversity, carbon footprint of solar, impact of wind power on landscapes and the consequences of its variability (“what happens if there is no wind overnight?”). Sense of ownership and governance also play a role: interest in self-generation and citizen participation in projects, deep differences of opinion about energy sufficiency and changing lifestyles, increased role of local authorities in energy policy... in sum, France is not the same country in 2021 as it was in the 1970s.

Lastly, the terms of the technical debate continue to evolve as well. When it comes to renewables, systems with a high percentage of renewable sources are the subject of research in many countries. RTE published a report in January 2021, in conjunction with the International Energy Agency (IEA), outlining the technical prerequisites for a system to operate with a dominant share of renewables in the mix, paving the way eventually for all-renewable systems. These scenarios include major technical challenges, notably the optimal integration of hydrogen. As for nuclear, the options on the table also appear to be broader: alongside large reactors like the EPR 2, more and more emerging projects involve small modular reactors (SMRs) and new technologies. The consultation for *Energy Pathways to 2050* highlighted that as of today, France does not have the capability to build nuclear reactors at the same pace as in the 1980s.

5 The power system of the future will necessarily be different to today's

In preparing the debate about these options, RTE started by defining a clear methodology centred around the distinction between two sets of scenarios representing societal trends observed in France today, depending on whether new investments in generation capacity focus exclusively on renewables ("M" scenarios) or a more technologically diverse mix combining renewables and new nuclear reactors ("N" scenarios).

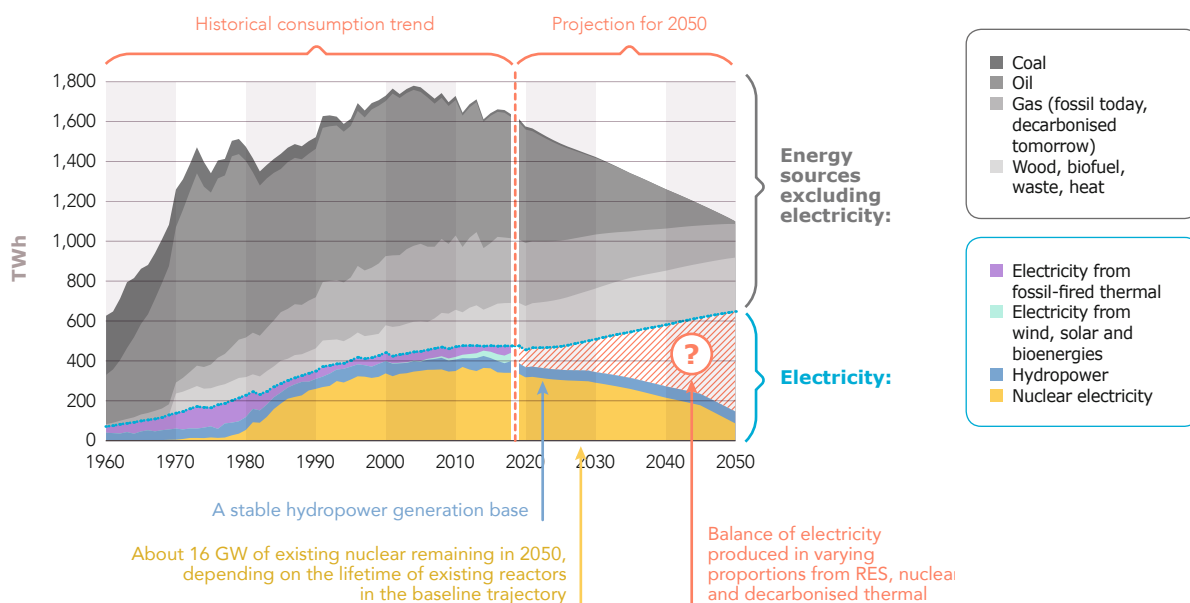
This representation underscores the importance of the decision about whether or not to launch a nuclear revival programme, which will commit the country to a long-term path and be the result of a policy choice with far-reaching technical, economic and societal implications. The approach was largely supported by the consultation. It results in the description of two types of power system that are different to the one in place today and will both require massive investments. However, **this should not be the only lens through which the scenarios are considered: indeed, drawing**

too sharp a contrast between the M and N scenarios would overshadow their significant similarities, both technical (high share of variable renewables, significant need for flexible capacity) **and economic** (preponderance of investment costs over operating costs).

All scenarios require envisioning a power system that is fundamentally different to the one in place today. Whether 100% renewable or relying over the long term on a combination of renewables and nuclear, the system will not operate based on the same principles as the one France has known for the past 30 years, and it cannot be designed as a simple variant of the current system.

The purpose of *Energy Pathways to 2050* is to describe these possible outcomes based on an in-depth technical study, economic forecasts, an environmental assessment, and consideration of societal factors.

Figure 3 Trend in total electricity consumption and final energy consumption for other energies in France



CONSUMPTION TRAJECTORIES

OUT TO 2050

Final electricity
consumption
per sector

 Industry
 Residential

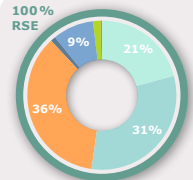
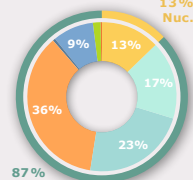
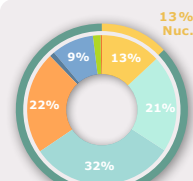
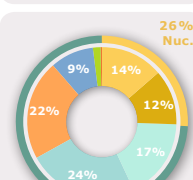
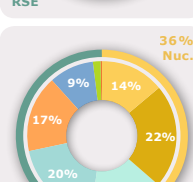
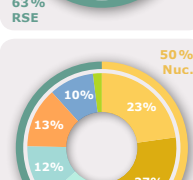
 Tertiary
 Transport

 Hydrogen

SCENARIOS			
	ASSUMPTIONS	LEVEL 2050	KEY CHANGES
Baseline	Gradual electrification (substitution for fossil fuels) and ambitious targets for energy efficiency (NLCS assumption). Assumes continued economic growth (+1.3% per year from 2030) and demographic growth (INSEE's low fertility scenario). The baseline trajectory assumes a high degree of efficacy of public policies and plans (stimulus, hydrogen, industry). The manufacturing industry expands, and its share of GDP ceases to decrease. Building renovation is factored in but so is the related rebound effect.	645 TWh	 180 TWh  134 TWh  113 TWh  99 TWh  50 TWh
	ASSUMPTIONS	LEVEL 2050 (vs. baseline)	KEY CHANGES (+ difference vs. baseline)
Sufficiency	Lifestyles change to increase energy sufficiency in terms of end-uses and consumption (less individual travel favouring soft mobility and mass transport, less consumption of manufactured goods, sharing economy, lower set point temperatures for heating, increase in remote working, digital sustainability, etc.), resulting in an overall reduction in energy needs, and thus electricity needs.	555 TWh (-90 TWh)	 160 TWh (-20 TWh)  111 TWh (-23 TWh)  95 TWh (-18 TWh)  77 TWh (-22 TWh)  47 TWh (-3 TWh)
Extensive reindustrialisation	Without returning to the same level as the early 1990s, the manufacturing industry's share of GDP rebounds sharply, reaching 12-13% in 2050. This scenario models an investment in cutting edge, strategic technologies and takes into account the reshoring of some high-carbon production in order to reduce the carbon footprint of consumption in France.	752 TWh (+107 TWh)	 239 TWh (+59 TWh)  134 TWh (0 TWh)  115 TWh (+2 TWh)  99 TWh (0 TWh)  87 TWh (+37 TWh)
VARIANTS			
Rapid electrification	The share of electricity in final consumption increases more sharply than in the NLCS. Some end-uses switch over more quickly or more largely to electricity. This is particularly the case for the transport sector, where electric vehicle adoption and the electrification of certain categories of heavy trucks happen much more rapidly. The switch to electric heating is also faster and more proactive.	700 TWh (+55 TWh)	 192 TWh (+12 TWh)  139 TWh (+5 TWh)  120 TWh (+7 TWh)  125 TWh (+27 TWh)  50 TWh (0 TWh)
Less electrification	The share of electricity in final consumption increases less largely and less quickly than in the NLCS. In industry, for instance, electricity does not become competitive and the transition to electrification is slower. The same is true of the transition to electric mobility (light and heavy vehicles) and the switch to electric heating in the residential and tertiary sectors.	578 TWh (-67 TWh)	 150 TWh (-30 TWh)  126 TWh (-8 TWh)  107 TWh (-6 TWh)  81 TWh (-18 TWh)  50 TWh (0 TWh)
Less energy efficiency	Generally anticipated advances in the energy efficiency of electrical equipment fail to materialise, or result in more consumption than that assumed in the baseline trajectory. In the building sector, targets set for renovation and conversion to heat pumps are not met, and the efficiency potential tapped does not exceed 50% in 2050 (vs. 70% in the baseline trajectory).	714 TWh (+69 TWh)	 191 TWh (+11 TWh)  156 TWh (+22 TWh)  135 TWh (+22 TWh)  105 TWh (+6 TWh)  50 TWh (0 TWh)
Hydrogen	The development of decarbonised hydrogen production accelerates sharply, driving final demand for hydrogen up well above the baseline trajectory. Hydrogen is substituted for direct electrification in some sectors that are difficult to electrify (steelmaking, etc.) and for the use of biomass (heavy transport, industrial heat).	754 TWh (+109 TWh)	 164 TWh (-16 TWh)  134 TWh (0 TWh)  113 TWh (0 TWh)  93 TWh (-6 TWh)  171 TWh (+121 TWh)

GENERATION MIX SCENARIOS IN 2050

Tech:  Demand-side flexibility (excl. V2G)  New decarbonised thermal
 Vehicle-to-grid  Batteries

	NARRATIVE	GENERATION MIX IN 2050	INSTALLED CAPACITY IN 2050 (IN GW)*					MIX OF FLEXIBLE RESOURCES IN 2050
			 Solar	 Onshore wind	 Offshore wind	 Historical nuclear	 New nuclear	
M0 100% RES in 2050	Nuclear is phased out in 2050: the decommissioning of existing nuclear reactors is accelerated and the rate of development of solar, wind and marine energies is pushed to the maximum.		~208 GW (i.e. x21)	~74 GW (i.e. x4)	~62 GW	/	/	 15 GW  1.7 GW (1.1 M EV)  29 GW  26 GW
M1 Distributed	Very robust development of distributed renewable generation across the country driven in large part by solar. This development implies strong mobilisation on the part of local actors and governments.		~214 GW (i.e. x22)	~59 GW (i.e. x3,5)	~45 GW	16 GW	/	 17 GW  1.7 GW (1.1 M EV)  20 GW  21 GW
M23 Large RES	Very robust development of all renewable technologies, driven notably by the installation of large onshore and offshore wind farms. Focus on economic optimisation and the technologies and geographic areas with the highest efficiency to allow economies of scale.		~125 GW (i.e. x12)	~72 GW (i.e. x4)	~60 GW	16 GW	/	 15 GW  1.7 GW (1.1 M EV)  20 GW  13 GW
N1 RES + new nuclear 1	Launch of a programme to build new nuclear reactors, developed in pairs on existing sites every five years starting in 2035. Robust development of renewables to offset the decommissioning of second-generation nuclear plants.		~118 GW (i.e. x11)	~58 GW (i.e. x3,3)	~45 GW	16 GW	13 GW (i.e. 8 EPR)	 15 GW  1.7 GW (1.1 M EV)  11 GW  9 GW
N2 RES + new nuclear 2	Launch of a programme calling for the faster development of new reactors (a pair every three years) from 2035 with a gradual ramp-up. Renewable energy development continues but at a slower pace than in scenarios N1 and M.		~90 GW (i.e. x8,5)	~52 GW (i.e. x2,9)	~36 GW	16 GW	23 GW (i.e. 14 EPR)	 15 GW  1.7 GW (1.1 M EV)  5 GW  2 GW
N03 RES + new nuclear 3	The generation mix is evenly split between renewables and nuclear in 2050. This implies keeping existing nuclear power plants in service for as long as possible and proactively developing a diversified mix of new nuclear (EPR 2 + SMR).		~70 GW (i.e. x7)	~43 GW (i.e. x2,5)	~22 GW	24 GW	~27 GW (i.e. ~14 EPR + a few SMRs)	 13 GW  1.7 GW (1.1 M EV)  1 GW
Overlapping assumptions			 Hydropower ~22 GW	 Marine energies 0 to 3 GW	 Bioenergies ~2 GW	 Imports 39 GW	 PSH 8 GW	

*Energy quantities and shares are expressed in relation to the baseline consumption scenario.



18 KEY FINDINGS FROM THE STUDY

1

Reducing consumption through energy efficiency, and possibly energy sufficiency, is key to reaching climate targets

1 France's low-carbon strategy already relies heavily on energy efficiency

Like other European countries, France intends to achieve carbon neutrality by reducing final energy consumption. The NLCS calls for a 40% decrease in energy consumption by 2050, a much more ambitious goal than those of other European countries. It intends to meet this target despite anticipated demographic and economic growth, thanks to a marked improvement in energy efficiency.

This improvement will be driven first and foremost by a reduction in the unit consumption of equipment

made possible by technological advances (natural technical progress with household appliances and electronics, such as lighting, electrical goods and IT equipment). It will also be fuelled by proactive public policies (building renovation). These two drivers alone will bring consumption down by 200 TWh. Another factor will be the electrification of certain end-uses, which will automatically improve energy efficiency (electric vehicle efficiency is close to 90% compared with 25-35% for internal combustion engines).

2 Energy sufficiency could further reduce energy consumption, but would constitute an idea of society in itself

In addition to energy efficiency, the public debate has begun to focus on energy sufficiency.

An "energy sufficient" France would reduce its consumption below the baseline trajectory level: the estimates in *Energy Pathways to 2050* suggest that electricity consumption could be reduced by a further 90 TWh, or 15% (on top of gains resulting from energy efficiency).

Reaching this goal would require doing more than sharing slogans about the benefits of consuming less: energy sufficiency implies radical changes to how society lives and organises itself. This is why the consultation did not produce any agreements or clear paths forward: some groups believe sufficiency should be the first response to the environmental crisis, while others reject the very principle in the

name of individual freedom and the need to maintain a subjective level of "comfort".

Drivers of sufficiency were identified and quantified for each sector of activity (residential, business and retail, travel and industrial activities) to allow for an informed debate. They were inspired by the results produced by the Citizens Convention for Climate, and outline a specific "societal pact" that the research conducted by RTE does not seek to qualify, promote or discourage, but rather to document in relation to the carbon neutrality target.

None of these drivers can be taken for granted, and each one marks an inflection of symbolic representations: beyond relying on the willingness of some individuals, they outline a scenario that would require collective action in terms of organising society.

3 Managing consumption remains the key to ensuring that investments are adequate and sustainable over the long term

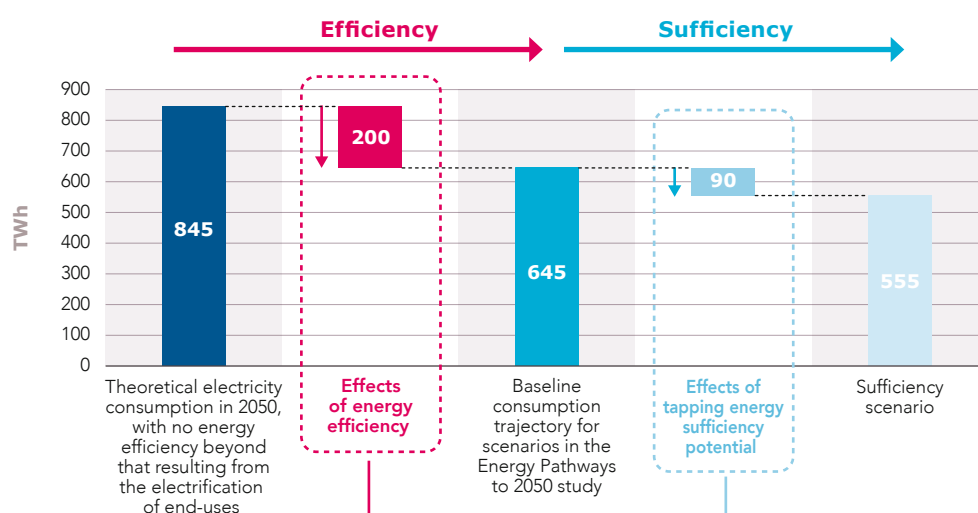
Several past RTE reports have underscored the importance of energy conservation to guarantee security of electricity supply while the system is transitioning, and also to reduce climate and environmental pressure on the energy system.

This is true of all the electricity mixes considered in *Energy Pathways to 2050*, even though electricity generation in France is already almost entirely decarbonised.

Reducing consumption makes it possible to slow down the required pace of reinvestment in the power system, eases pressure on resources, and makes the system more resilient to shocks of all kinds. **With the energy system set to enter a new investment cycle and electricity consumption likely**

to increase as fossil fuels are replaced, limiting the increase in electricity consumption will clearly be beneficial and even indispensable to ensure a successful transition. This is especially true considering the ambitious reindustrialisation plans on the table.

Key finding 1 Anticipated effects of energy efficiency and potential effects of sufficiency measures on consumption levels (relative to the baseline trajectory)



1 Reduction in the unit consumption of equipment: household appliances, lighting, IT equipment.

2 Adoption of ambitious public policies: thermal renovation of buildings (pace of renovations doubled), standards for new buildings (RE 2020 regulation), "tertiary decree", priority use of heat pumps.

3 Energy efficiency automatically resulting from electrification: electric vehicles and heat pumps have significantly higher efficiency than internal combustion engines and fossil fuel-fired boilers.



Residential: -23 TWh

increase in co-housing, voluntary limitation of consumption of heating (-1° C) and hot water.



Business and retail: -18 TWh

increase in remote working associated with a limitation of office space, less IT equipment.



Travel: -22 TWh

decrease in individual travel due to car sharing, reduction in average travel speeds and vehicle size.



Industrial activities: -20 TWh

reduction in needs of agri-food industry if less processed foods are consumed, reduction in production of goods thanks to longer equipment life.

2

Energy consumption will decrease but demand for electricity will increase as fossil fuels are replaced

Electricity is omnipresent in the lives of residents in France but it is not dominant in the country's energy mix as of today.

Its use is minimal in the transport sector (2%, versus 91% for fossil fuel energy), minor in building heating (16% versus 56% for fossil fuel energy with 4 million households using fuel oil boilers), and closer to parity in industry (36% versus 51%

for fossil fuels¹), which still relies heavily on hydrocarbons such as oil, gas and coal, as well as "grey hydrogen" from gas.

Therefore, to achieve carbon neutrality, it is necessary to reduce consumption and to power remaining consumption with low-carbon sources, such as electricity and biomass uses (wood energy, biomethane, biofuels, etc.).

1 Electricity consumption is expected to rise even factoring in a significant development of energy efficiency

Estimated trajectories for electricity consumption have been revised upward in recent years across the globe, notably in Europe, due to the adoption of more ambitious climate targets (-55% in 2030, carbon neutrality in 2050).

The guidelines adopted by France (in the NLCS, hydrogen plan, sector policies, etc.) would lead to a moderate 35% increase in electricity consumption over 30 years, implying a 1% average annual increase. Electricity consumption would reach 645 TWh in 2050 (baseline trajectory).

In contrast to the projections RTE published five years ago, in which fossil fuel energy still had considerable

weight since reaching carbon neutrality was not the objective at the time, current projections point to an upward trajectory. This evolution is part of a broader trend of revising electricity needs upward in accordance with the decarbonisation targets.

The increase projected in the baseline trajectory is moderate relative to numerous European scenarios leading to carbon neutrality. Indeed, the NLCS is underpinned by the principle of strong development of energy efficiency (automatically resulting from electrification, increasingly efficient household appliances, and sharp acceleration in the thermal renovation of buildings).

2 Demand for electricity will increase as it is substituted for fossil fuel energy

In most cases, new electricity end-uses stem from the replacement of fossil energy with electricity. The resulting transfer effect is particularly significant in areas where electricity is not widely used today: in transport (100 TWh in 2050, versus 15 TWh today), in industry (180 TWh versus 115 TWh today) and in hydrogen production (50 TWh versus 0 today). And it is only partially offset in the residential and tertiary sectors by thermal renovation and the energy efficiency resulting from natural replacement of electrical equipment (lighting, household appliances, etc.).

All carbon-neutral scenarios thus result in significant electrification of vehicles (94% of light vehicles and 21% of trucks in 2050) and industrial processes. Yet they do not create an "all-electric" society: in addition to electricity, gas (biomethane, hydrogen, different types of synthetic gas), liquid fuels (biofuels or synthetic fuels), wood and biomass (for heat) are all used as well.

1. Excluding use as a raw material

3 All scenarios, variants and sensitivity analyses point in the same direction

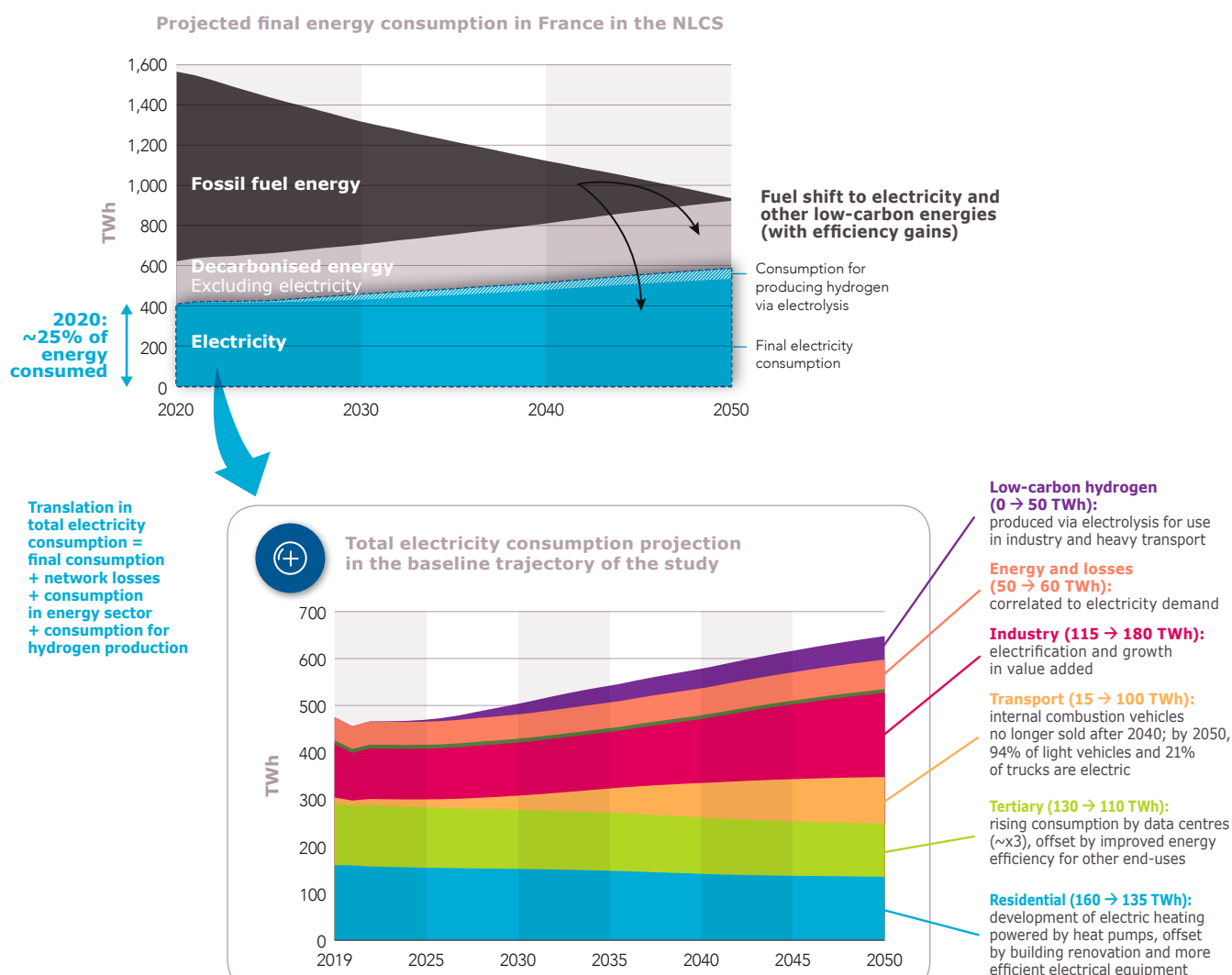
The scenarios in *Energy Pathways to 2050* do more than simply offer a baseline trajectory. They explore a large number of different configurations.

All variants and scenarios lead to an increase in consumption, ranging from 15% (sufficiency) to 60% (reindustrialisation or hydrogen+). It is possible to combine variants without changing this outcome. **The French power system must therefore have the capacity to absorb a very likely increase in electricity demand once the**

transformations required to achieve carbon neutrality begin, even if significant gains are indeed made in terms of energy efficiency and sufficiency.

Over the medium term, the new European targets (-55% net in 2030, *versus* -40% in the NLCS) imply more rapid action than in the baseline scenario. The corresponding trajectory ("Acceleration 2030") therefore requires electrifying end-uses at a faster pace.

Key finding 2 Trend in energy and electricity consumption on the road to carbon neutrality



3

Accelerating France's reindustrialisation by electrifying processes will increase its electricity consumption but reduce its carbon footprint

1 A scenario involving an industrial revival, supported by low-carbon energy, would have great benefits for the climate

Over the past 30 years, France has been able to reduce its domestic greenhouse gas emissions, while its carbon footprint (emissions generated domestically and emissions from other countries associated with imported goods) has shrunk only marginally. This paradox reflects the country's deindustrialisation and growing reliance on imports of manufactured goods to keep up with rising consumption in France.

The phenomenon is counterproductive from a climate standpoint, bearing in mind that France has access to low-carbon electricity and has one of the best performances in the world in this area. A return of industrial development, involving targeted investments in cutting-edge industries and activities that

can help reduce the country's carbon footprint, is one way to address this challenge: in *Energy Pathways to 2050*, it is studied in the "extensive reindustrialisation" scenario.

This scenario requires rebuilding France's production capacity around low-carbon solutions starting with the next investment cycle.

It will depend on how competitive the French system is price- and carbon-wise relative to the carbon-based alternatives available outside France, and in this regard is a high-stakes issue. Under this scenario, the manufacturing industry would eventually account for roughly the same share of GDP as in the early 2000s, and the trade balance would be very positive.

2 In a reindustrialised economy, the rise in electricity consumption will exceed that factored into the baseline trajectory

Because France imports much more than it exports, the energy and environmental consequences of domestic consumption are only partly visible in its energy and climate balances. With reshoring, the consequences will be tangible: RTE estimates that a reindustrialisation scenario would push electricity consumption up about 100 TWh above the baseline trajectory, potentially causing it to reach 750 TWh.

To keep up with such developments, **the power system must be ready to accommodate a bigger increase in electricity demand** (+60%, versus +35% in the baseline case). France is largely a net electricity exporter today, and that situation could be capitalised on over the next ten years, allowing time for new investments in low-carbon electricity generation to bear fruit.

3 In a reindustrialised economy, France's carbon footprint would shrink considerably

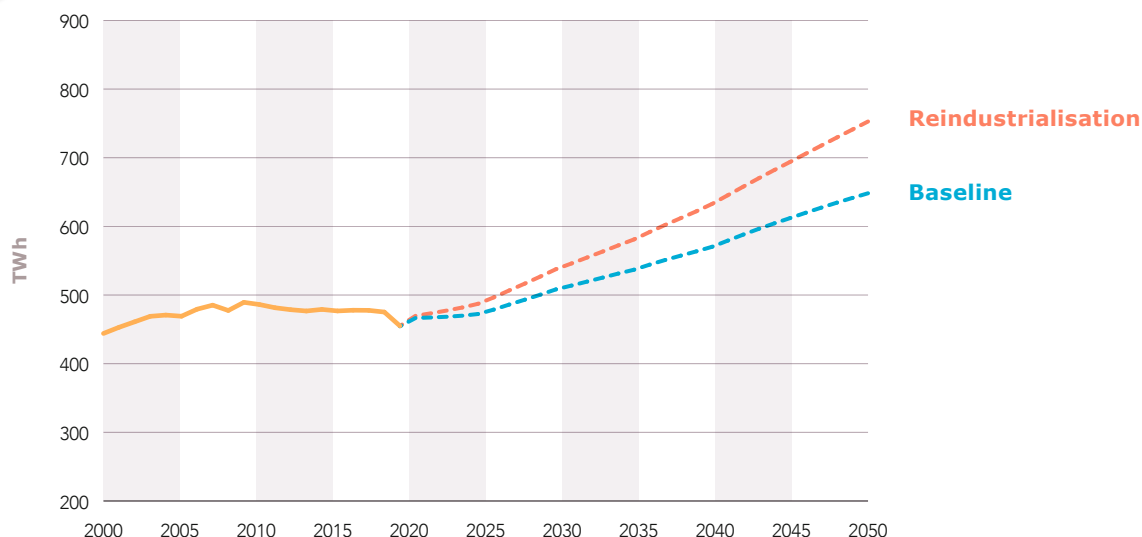
Reindustrialisation would drive a very substantial decrease in France's carbon footprint, this being one of the biggest challenges it faces in its fight against climate change, given its negative trade balance. **Extensive reindustrialisation would help avoid the emission of some 900 million tonnes of CO₂ over 30 years, with gains ramping up at every stage of the trajectory: ~10 MtCO₂eq/yr between**

2020 and 2030, ~30 MtCO₂eq/yr between 2030 and 2040, ~40 MtCO₂eq/yr between 2040 and 2050.

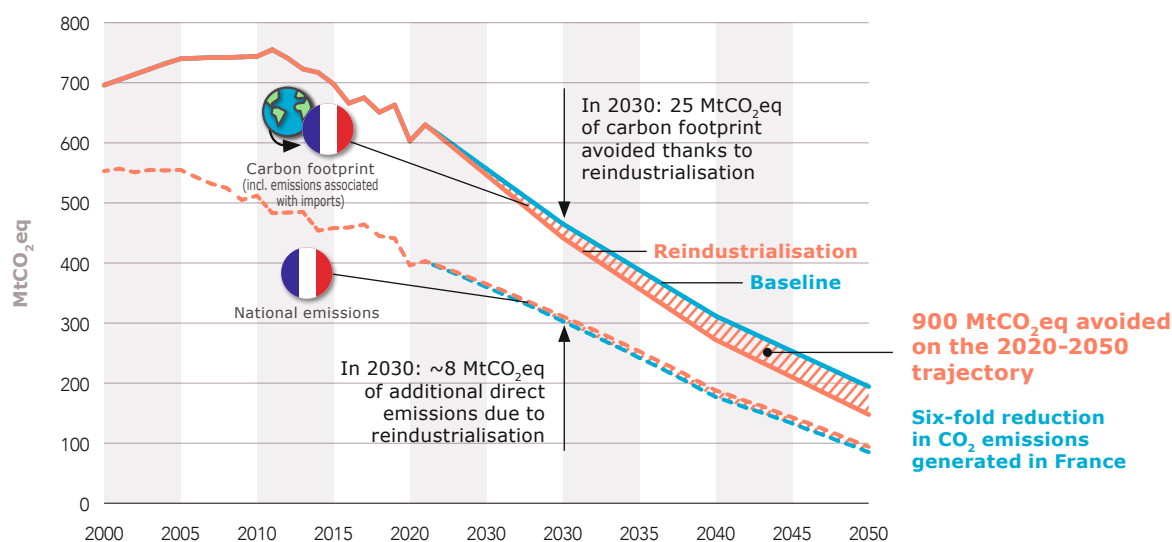
The fact is that France can take advantage of its more decarbonised current mix and the achievement of more ambitious climate goals than those of most countries from which it imports manufactured goods.

Key finding 3 Effects of extensive reindustrialisation on electricity consumption in France and its carbon footprint


Projected trend in electricity consumption in France with or without extensive reindustrialisation



Effects of the extensive reindustrialisation scenario on France's domestic emissions and carbon footprint



4

Carbon neutrality cannot be achieved by 2050 without significant renewable energy development

To achieve carbon neutrality by 2050, France will need to generate more electricity than it does today, while also replacing the majority of the power plants that make up its existing fleet (first-generation

nuclear and renewables). In other words, most of the generation capacity that France will rely on for electricity in 2050 does not exist today.

1 Maintaining a significant nuclear fleet over time will result in massive decarbonisation, but will not nearly suffice to reach carbon neutrality

Thanks to its nuclear fleet, France's greenhouse gas emissions are significantly lower than in neighbouring countries. From an industrial standpoint, changes in the nuclear fleet over the long term will be constrained by two factors:

- (1) regardless of policy preferences, the lifespan of second-generation reactors cannot be extended indefinitely: the plants operating today, the majority of which were built in the 1980s, will need to be shut down by 2060, setting the stage for a sudden and drastic reduction in nuclear capacity in the 2040s;
- (2) if the decision is made today to build new reactors (Generation 3), they would not be commissioned before 2035 at the earliest, with a new pair coming online every four years. Any decision made today to speed up the commissioning of new plants would not produce any notable effects before 2045.

These constraints were discussed with actors in the nuclear sector, who had a chance to express their views during the public consultation. **The most ambitious industrial proposal from the nuclear sector to date involves having a nuclear fleet with total capacity of 50 GW in 2050 (N03 scenario) assuming a proactive nuclear revival programme².**

Despite current nuclear capacity, achieving this goal presents a major industrial challenge. Having 50 GW of nuclear capacity in 2050 will require extending the lifetime of most existing reactors to 60 years; having the option of keeping some in operation beyond that timeframe subject to compliance with safety recommendations from the ASN; bringing 14 new EPR 2 reactors into service between 2035 and 2050, a large number of them between 2040 and 2050; and adding significant SMR capacity at the same time.

This forecast will probably evolve over time: with no reinvestment in the nuclear industry, its assumed long-term capacity will continue to decrease, whereas a decision in the near term to revive the technology could subsequently result in an upgrade to the forecast.

It can be assumed that nuclear capacity of 50 GW could produce about 325 TWh a year by 2050. Under the baseline trajectory, this would represent about 50% of the country's total generation. Its relative share of total generation would vary depending on the consumption scenario, ranging from 60% under the "sufficiency scenario" to 44% under the "extensive reindustrialisation" scenario.

2 In all cases, it will be absolutely essential for France to develop significant renewable energy capacity to achieve carbon neutrality

Even a nuclear fleet that includes reactors operating with an extended lifetime, together with a large number of new reactors, will not be able to keep up with consumption if it reaches 645 TWh in 30 years' time, and even less if it reaches 750 TWh.

The study makes it very clear that robust development of renewable electricity is a prerequisite if France is to uphold its climate commitments.

2. By comparison, the existing fleet, including the EPR reactor in Flamanville, represents installed capacity of 63 GW

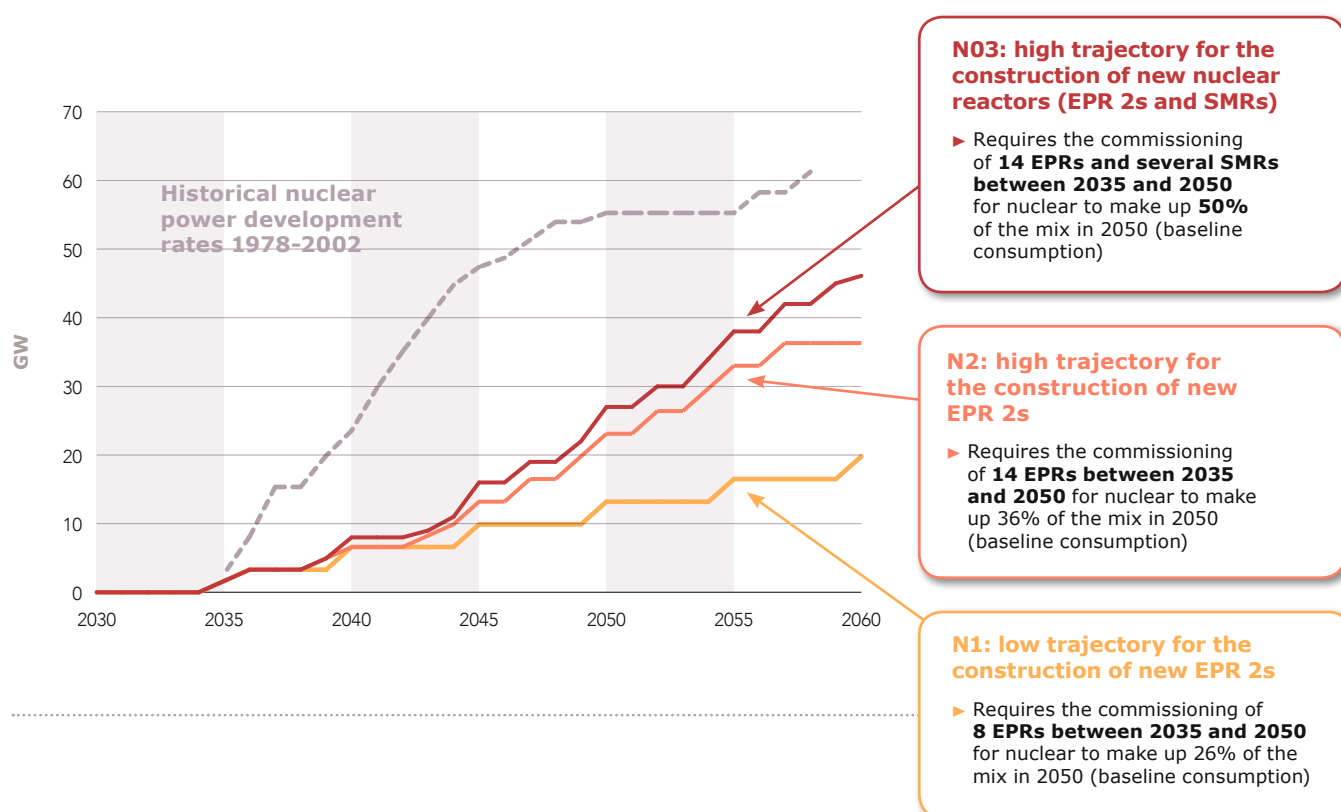
To meet those commitments, renewables must be developed wherever possible: solar, onshore and offshore wind, and of course hydropower, the remaining growth potential of which must be tapped when environmental standards so allow.

All European scenarios call for robust development of solar power, and France is no exception: over the next 30 years, solar capacity will need to be increased to at least 70 GW (and to more than 200 GW in the highest trajectory). These figures are not very different from forecasts for neighbouring countries, though they do imply impressive growth from today's relatively low level (10 GW versus 13 in the United Kingdom, 14 in Spain, 21 in Italy and 54 in Germany).

Meeting climate targets will also necessarily require developing wind power, now a mature

technology with low production costs that can be relied upon to produce significant quantities of electricity. It will be possible to adjust the split between onshore and offshore wind based on the economic opportunities that arise and acceptability issues, but it seems that France will need to develop at least 40 GW or so of onshore capacity and to have offshore capacity of about 25 GW. While there would be no economic or technical obstacles to reaching these levels (except where floating wind turbines are concerned), acceptability could be a concern, though the results achieved by other European countries should be borne in mind: Germany has developed 50 GW of onshore wind capacity in 15 years, Denmark has installed 4.5 GW knowing that its surface area is less than 8% that of mainland France, and the United Kingdom built up offshore wind capacity of 10 GW over 20 years, and will lift that capacity to 20 GW by 2030.

Key finding 4 Trajectories for the development of new nuclear reactors envisaged in the study



5

Without new nuclear reactors, renewable energy will need to be developed at a pace exceeding that seen in the most dynamic European countries

1 The “100% renewable” scenarios require a high degree of acceptance of renewable energies and a very sharp uptick in development rates

The minimum renewable development rates that will allow carbon neutrality to be achieved are high relative to what France has experienced in the past decade. Those that would become necessary in scenarios where nuclear is phased out are even higher. They raise questions about France’s ability to develop the necessary wind and solar capacity given the need to gain acceptance from local populations and overcome potential industrial obstacles in certain sectors.

In terms of acceptance, each technology raises a different set of issues. In all cases, the density of onshore wind turbines (next generation) across France in 2050 would be lower than what is currently observed in Germany, yet the technology remains the subject of lively debate about its impact on landscapes, and many projects are being challenged. Offshore wind is just starting to be developed, but already questions are being raised about how it will coexist with other uses such as fishing. Lastly, when it comes to large solar farms, some wonder about the possibility of future conflicts with agriculture or the use of natural spaces. **The bottom line is that the scenarios calling for nuclear to be phased out require a favourable political and societal “climate” in terms of acceptance of renewable energy infrastructure.**

From an industrial standpoint, the pace of development of renewable energy sources accelerates

sharply in all scenarios without new nuclear reactors, especially for solar and offshore wind. **The M0 scenario, which calls for nuclear to be phased out by 2050, would pose a huge industrial challenge since the resulting renewable energy development rates would largely exceed the cumulative totals of recent years for onshore renewables in Germany and offshore wind in the United Kingdom.** Even under the “sufficiency” scenario, the development rates necessary for the M0 scenario to play out remain very high.

The same is true of the M1 (for solar) and M23 (for offshore wind) scenarios. **Even a scenario calling for a nuclear revival with a minimum programme of six reactors would require particularly robust renewable growth rates.**

On the other hand, the N2 and N03 scenarios, which are based on a substantial nuclear fleet being maintained over the long term, are compatible with average historic development rates in France (for onshore wind) or the trajectories set out in the Multiyear Energy Plan for the coming years, which foresee accelerated development (for solar and offshore wind). As of today, however, France is not completely on track: the N2 and N03 scenarios also assume a proactive approach to installing more renewable energy capacity.

2 Across the globe, there are many carbon neutrality strategies not based on a “100% renewable” power system

While several European countries have adopted strategies based on electrification and an all-renewable power system, many others have plans that include complementing local renewable energy production. Germany has a short-term strategy that relies largely on gas imports and a longer-term one based on imports of “green hydrogen”; several countries along the North Sea plan to continue to use fossil fuels but with carbon capture and storage solutions (CCS); and the United Kingdom, the United States and China have launched programmes

to build new nuclear plants to be used alongside renewables.

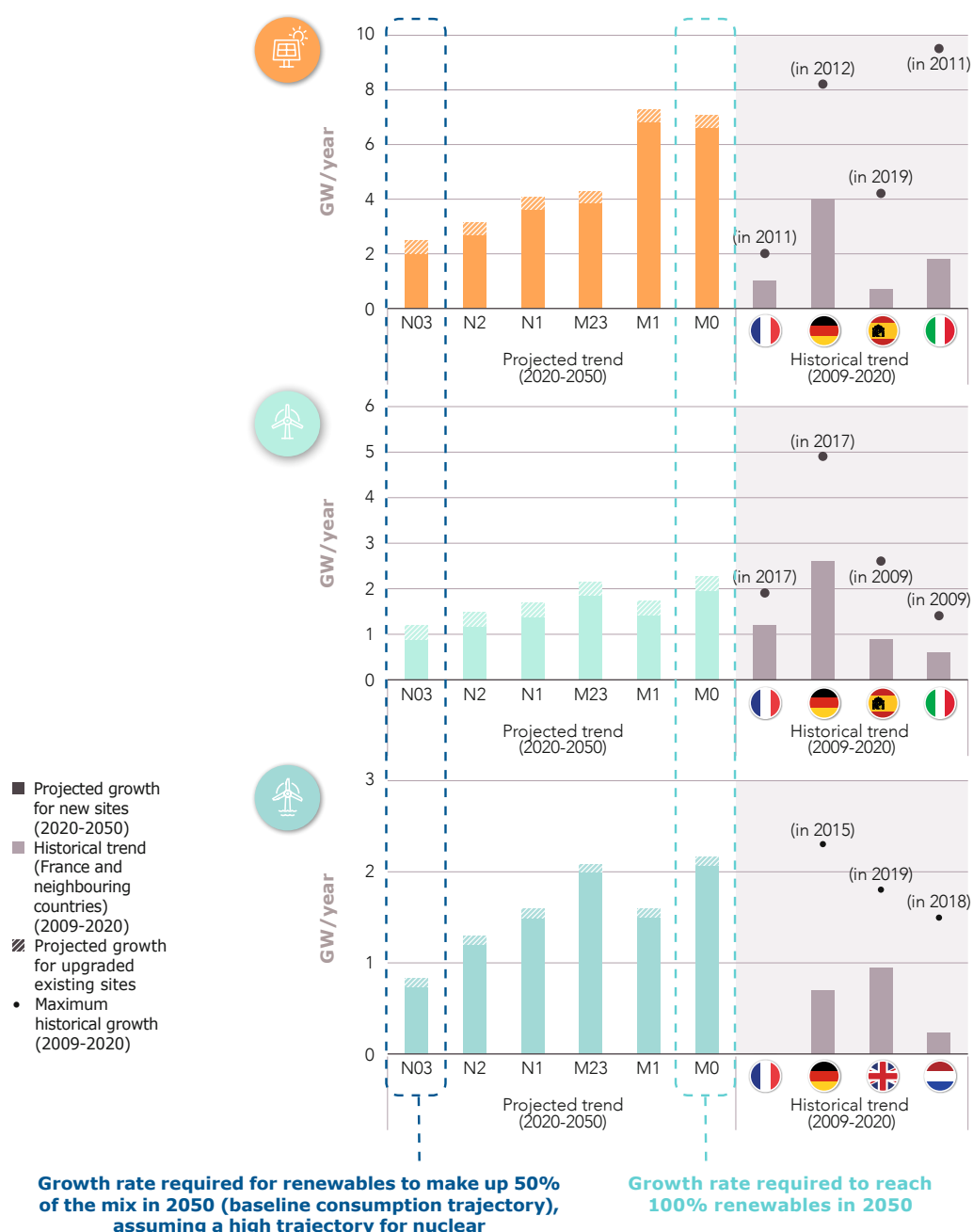
This complementarity is also found in IEA and European Commission scenarios. In particular, the IEA’s latest net zero scenario includes nuclear or CCS, though in proportions below 50%.

Technical analyses for France show that phasing out nuclear would create a significant extra constraint for reaching carbon neutrality. **This constraint could**

only be lifted by sharply accelerating wind and solar development rates, by activating all the energy sufficiency levers listed in the RTE scenario, or by eliminating certain characteristics

of the NLCS, such as the quest for substantial energy independence (which would mean relying on imports of low-carbon energy products, assuming they can be produced elsewhere).

Key finding 5 Required renewable energy development rates under different scenarios (applying the baseline consumption trajectory) vs. historical trends and vs. neighbouring countries (GW/yr)



6 Building new nuclear reactors makes economic sense, particularly if it allows a 40 GW fleet to be in place in 2050 (existing plus new nuclear plants)

1 Economic space exists for building new reactors

The study concludes with a fair degree of confidence that the scenarios that include a nuclear fleet of at least 40 GW (N2 and N03) may, over the long term, result in lower costs for society than one based on 100% renewables and large energy farms.

This is true even if “gross” production costs are higher on average for new nuclear plants than for large renewable energy farms. Indeed, the integration of large quantities of wind turbines or solar panels creates a very significant need for flexible resources (storage, demand side management and new backup plants) to offset their variability, as well as for grid strengthening (connection, transmission and distribution). Once all these costs are factored in, the scenarios that include new nuclear reactors appear more competitive.

The effect is even more pronounced when the nuclear fleet considered is significant enough (close to 40 GW in N2) to avoid the costs associated with a power-to-gas-to-power loop in France and massive grid strengthening.

This advantage would be greatly reduced, but still exist, if the cost of new reactors did not decrease and remained close to that of the Flamanville EPR.

The M scenarios (100% renewable) appear much more expensive than the N scenarios when nuclear is phased out rapidly (2050 in the M0 scenario) or when large wind or solar farms do not make up the bulk of capacity (M1 scenario, including more small solar systems).

2 Their economic advantage will depend on whether the terms of available financing are comparable to those of other low-carbon technologies

Building new nuclear reactors is a very capital-intensive undertaking. Construction times and service lives are long. As a result, their competitiveness is very dependent on financing costs, in other words on the cost of capital.

Unfavourable financing terms may for instance reflect an absence of government support or greater

challenges in accessing European funding, factors that would drive up the full cost of nuclear generation, which would in turn impact total power system costs. If the difference represented three percentage points, then the cost of a scenario that includes new reactors would be equivalent to a “100% renewables” scenario with the best economic outcome, i.e. one based on the construction of large farms (M23).

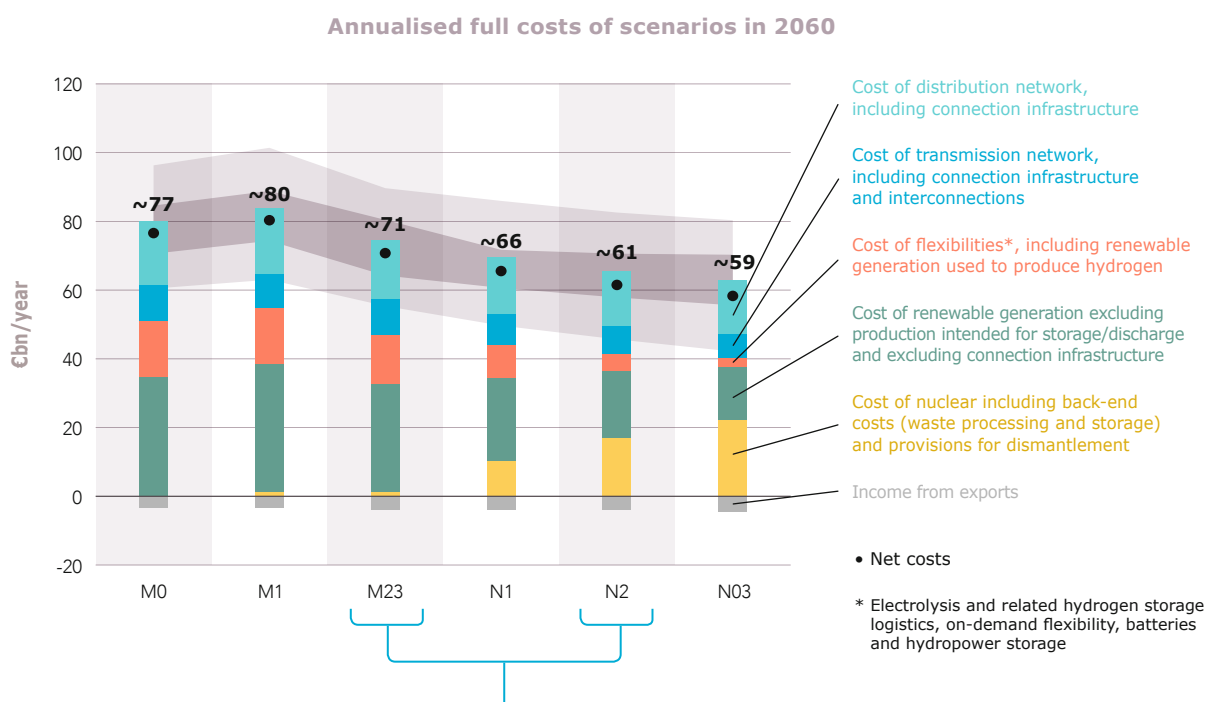
3 The economic advantage is visible in almost all variants

Regarding the evolution of technology costs, under the baseline scenario, the cost difference between the M23 and N2 scenarios is close to 10 billion euros a year. However, there is major uncertainty as to where costs will stand in this timeframe, not only for nuclear but also for renewables and storage solutions. This makes it necessary, from a methodological standpoint, to analyse a large number of variants and stress tests to identify the least regret options.

RTE’s analysis shows that the difference between the economic costs of M23 and N2 are comparable in the very large majority of configurations tested, including for cases in which costs or financing terms are unfavourable for new nuclear. Conversely, the competitiveness of the scenarios with a high share of renewables depends on several factors including the economic performance of developing floating wind turbines: if that performance is poor, the difference is even greater.

Key finding 6

Full costs (production + transmission + flexibility) in France per scenario (based on the baseline consumption trajectory) **in 2060**, for central scenario and variants



Trend in the difference between annualised full costs of the scenarios with different variants (€bn/yr)



7

Renewable electricity has become a competitive solution. This is especially true in the case of large solar plants and onshore and offshore wind farms

1 The costs associated with a 100% renewable scenario factoring in large renewable energy farms may be comparable to a scenario that includes new reactors, as long as an efficient and flexible “hydrogen system” is available and floating wind power is a success

Thanks to the renewable energy policies adopted in different parts of the world in recent years, large wind and solar farms have become much more technologically mature: **their costs are very competitive today, and have fallen below those of new thermal and nuclear power plants.**

Over the longer term, the costs associated with a system comprised of 100% renewable energy may approach those of a system that includes new nuclear reactors, provided that several conditions are met:

(i) Promotion in priority of the most mature technologies and the development of large farms to enable economies of scale;

- (ii) Success of floating offshore wind power, with cost decreases similar to those observed in recent years for fixed foundation turbines;
- (iii) Favourable financing terms for renewable energies with, at minimum, continued government support via feed-in tariffs and premiums schemes;
- (iv) Control of the cost of flexibilities and notably the cost of the system necessary to offset the variability of wind power: a competitive and mutualised “hydrogen system” (storage and network), possible occasional recourse to biomethane if it is sufficiently developed, etc.

2 The development of large renewable energy projects leads to an economic advantage when it does not result in significant development of flexibilities

As long as flexibility needs remain fairly limited, as is the case today, there are real economic benefits to developing renewable energy sources: the full cost of generating energy from renewable sources relative to their production is lower than for new nuclear reactors.

Increasing the share of renewables in the energy mix from the current level is thus not only necessary for industrial and climate reasons: it also makes good economic sense.

Yet this economic advantage shrinks, and eventually disappears, as the need for flexibilities emerges and increases. The simulations conducted for *Energy*

Pathways to 2050 show that these needs materialise first in neighbouring countries, where the share of wind and solar power is higher than in France.

In France, the economic analysis shows that the gain associated with an expansion of the nuclear fleet from 40 GW (N2 – i.e. nuclear covering about 36% of baseline consumption) to about 50 GW (N03 – close to 50% of baseline consumption) is small in most of the configurations considered, and may depend on multiple parameters. Additional analyses must be conducted to establish the exact tipping points, which also depend on the level of interconnections between France and neighbouring countries.

3 The scenarios that call for phasing out nuclear by 2050 (M0) or rely primarily on distributed solar (M1) are significantly more expensive than other options

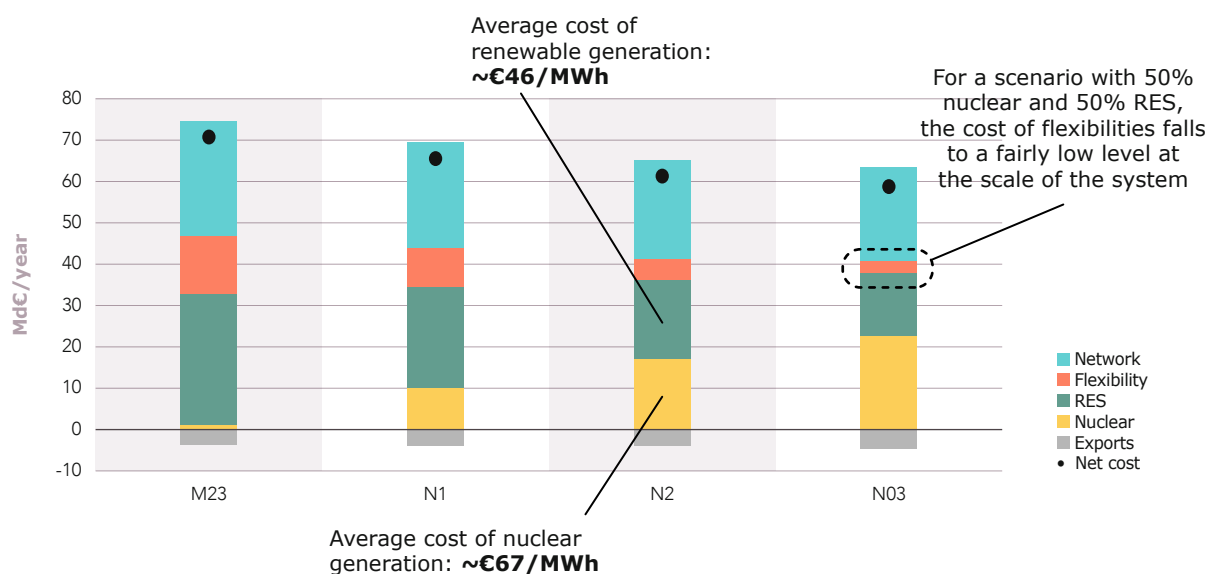
Aiming for 100% renewable power in 2050 (M0 scenario) is costlier at every stage of the trajectory. This is because renewable energy development starts earlier, eliminating the chance to benefit fully from continued cost decreases for these technologies, and because existing nuclear reactors are shut down ahead of schedule.

Achieving 100% renewables by 2060 (M1), but opting for a mix of distributed renewable sources, drives up production costs since roof-mounted solar is more expensive than large ground-mounted solar farms or wind farms, and requires installing more batteries.

The fact that generation is distributed more evenly across the country does slightly reduce transmission grid costs, but also drives up distribution grid costs slightly.

That being said, the analysis conducted on M1 does not invalidate the goal of developing self-consumption for consumers or the benefits of seeking a better balance between production and consumption: more research into M1 will thus be necessary as part of the additional analyses planned for early 2022.

Key finding 7 Annualised full costs in 2060



* Central assumption for technology costs and a cost of capital of 4%

The system will require very different types of flexibilities to ensure security of supply in the different scenarios. There is an economic case for increasing demand-side management, expanding interconnections and hydropower storage, and installing batteries to support solar power. Additionally, new thermal power plants fuelled by decarbonised gas (including hydrogen) will be necessary if the nuclear revival is minimal. This need will be massive – and thus very costly – if the system moves toward 100% reliance on renewables.

Whatever decision is made about a new nuclear programme, the power system of the future will rely in large part on variable renewables. It will have to manage regular day-night cycles (for solar) as well as wide variations in wind power production over a given week, month, or even year. This will pose a major technical challenge.

For such a system to function, “flexibilities” must be developed. Flexibility is a generic term and can easily be presented as a solution everyone can get behind, especially as its exact meaning is rarely defined. Yet the technologies, temporalities and costs being considered can vary greatly.

The need to develop flexibilities is to a large extent common to all scenarios and has political and organisational consequences. Digital will play an increasingly important role in managing in real time a complex power system comprising generation resources that are more widely dispersed and dependent on weather conditions, which creates new risks (cybersecurity, data management). Greater interdependence will exist between the different regions of France as well as at the European level: rather than creating a more “decentralised” system, growth in renewables will result in even greater mutualisation. Lastly, making the system more flexible will require building new infrastructure – both grids and storage, from small distributed batteries to new plants fuelled by decarbonised gas.

1

Increasing interconnection capacity between France and its neighbours is a significant source of savings, implying a degree of interdependence between European partners

The more interconnected the system is, the less flexibility needs to be guaranteed in each area comprising it: this technical reality substantially improved the efficiency of the French power system in the 20th century, and may be reinforced at the European level over the coming years, to the benefit of French consumers.

Looking ahead to 2050, 39 GW of import capacity (against 13 GW today) is a good compromise between the economic optimum and technical and political realism.

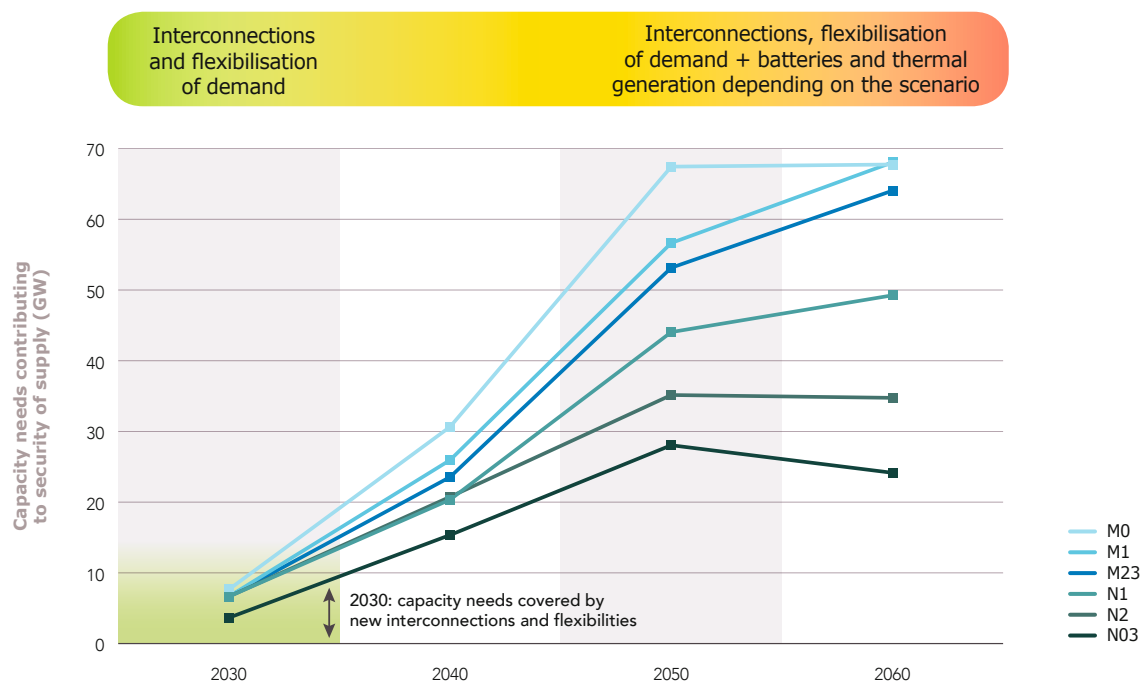
While interconnections facilitate the integration of large quantities of renewable energy, in exchange, they require accepting the principle of interdependence at the European level (France’s security of supply would depend on its neighbours 5% of the time, versus 1%

today) and good coordination of energy policies (as the volume and type of backup capacity to be installed in France would also depend on the situation in neighbouring countries). **At the same time, France’s dependence on oil- and fossil gas-producing countries would be eliminated: carbon neutrality scenarios are indeed scenarios that imply substantially increasing energy independence.**

The expansion of interconnections is a proposal resulting from the economic analysis, but it is not an obligation. Other trade-offs are possible: lesser interdependence, but with higher system costs. Whatever choice is made, cost differences between the generation mix scenarios tested remain of the same order of magnitude.

Key finding 8

Trend in the need for new flexible capacity to increase security of supply (in addition to the flexibility intrinsic to nuclear and renewable generation facilities)



2 Building new thermal power plants fuelled by decarbonised gas is necessary in scenarios without a proactive nuclear revival

Extensive development of renewable energy sources like wind and solar power cannot be envisaged without having dispatchable resources available as well. In particular, the system must be able to operate by releasing energy if there is no wind for several weeks in a row, which cannot be guaranteed by batteries or smart demand management. Hydropower reserves will not suffice to meet this need, and there is no other way to cover it than with nuclear plants or thermal power plants fuelled by decarbonised gas.

Building new decarbonised thermal power plants is a technical necessity in these scenarios. In France, the smaller the nuclear fleet becomes, the greater

the need will be. It becomes massive in the 100% renewables scenarios or if the nuclear revival is weak: about 30 GW, which would be more thermal power plants than France has had since the 1970s (it currently has 16 fossil gas-powered plants). On the other hand, it may be avoided in robust nuclear revival scenarios if interconnections with the European power system are significant and fluid.

Note that these plants will operate infrequently: they will serve as backup capacity in case other types of generation are unavailable.

3 Hydropower storage, demand-side management and batteries are useful solutions to manage fluctuations on a daily or weekly scale

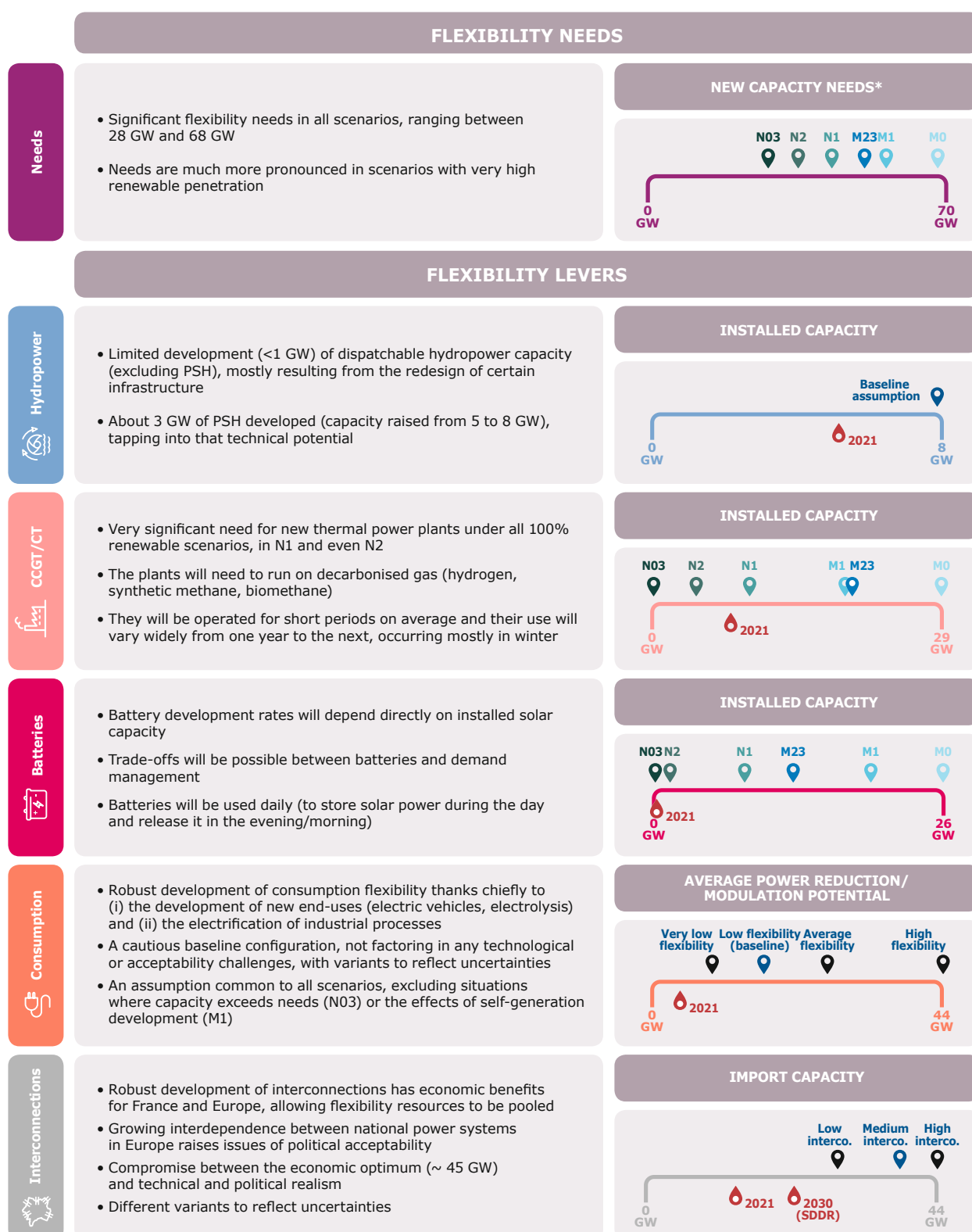
The development of pumped storage hydropower (PSH) and smart demand management (in buildings and transport via smart electric vehicle charging) are two “no regret” solutions from a technical and economic standpoint: they are profitable in all situations. Any related challenges are thus of a different nature (environmental impact for hydropower, political and societal acceptability for demand management).

There are benefits to taking full advantage of the flexibility and even storage potential afforded by electric vehicles. The primary way to tap this potential is

with smart vehicle charging (during the day, when solar production is high, as well as weekends and overnight with systems that switch on automatically when vehicles are not in use): the benefits for consumers and the system are real, and come at no extra cost. Beyond that, using batteries for storage (vehicle-to-grid) is another option, but not a necessity in most of the configurations considered here

Using large batteries dedicated to the power system for storage is a very appropriate solution in scenarios in which solar power is widely used. Yet it is not indispensable in all scenarios.

Key finding 8 Overview of flexible capacity requirements to contribute to security of supply in 2050 (baseline consumption trajectory)



* Flexibility needs are expressed in "perfect" GW (always fully available with no activation constraints)

Under all scenarios, the power grid will need to be adapted rapidly to make the energy transition possible

1 Networks are a cornerstone of the energy transition

The public debate on the power sector is focusing primarily on generation resources, but in reality, the network is the heart of the sector: all generation sources and consumption sites are always connected to a grid, and the need for equilibrium between supply and demand at all times is not found in any other industry. Any generation, storage or consumption sites added must be connected to the grid and may require adaption thereof. This is why networks play such a key role in the energy transition equation.

For the energy transition to happen, the transformation of these networks will need to accelerate. The industrial dynamics and financing driving this transformation must by their very nature be viewed on a long term. When a major new piece of infrastructure is added, it takes several years to complete the studies

and secure authorisations based on urban planning rules, environmental laws, and energy sector policy. Once construction is complete, some infrastructure may remain in service for more than 80 years if regular and appropriate maintenance is performed.

New grid connections will increase over the coming years, and the accelerated pace will pose a technical and organisational challenge for stakeholders (local authorities, industrial sector, producers, associations).

This transformation will be taking place in a societal context where rapid progress is demanded, while at the same time systematic opposition is appearing, including when the infrastructure is vital to the energy transition. The result is a paradox.

2 Transmission network: structural changes starting in 2030, much more significant in the 100% renewables scenarios

RTE published its Ten-Year Network Development Plan (*Schéma décennal de développement du réseau – SDDR*) in 2019, and it has since been approved by the energy minister and by CRE. It calls for 33 billion euros to be invested over 15 years to create a grid that can accommodate the mix called for in the Multiyear Energy Plan and to begin replacing infrastructure, some of which was built right after the Second World War.

This will only be a first step: changes will accelerate beyond 2030, both to adapt the network to the evolution of the electricity mix and to replace its oldest components.

If France moves towards a system with a high share of renewable energy, major upgrades to the network will be necessary: new north-south and east-west energy highways, more interconnections, connection of large offshore wind farms (fixed foundation or floating). At the same time, investments required to replace the oldest infrastructure (lines built in the 1950s and 1960s) will continue to rise.

The timeline set forth in the Ten-Year Network Development Plan must in all scenarios be adhered to, and even sharply accelerated in the M scenarios as well as in N1, in which the pace will need to more than double.

3 Distribution network: the cost of adaptations will increase to keep up with rising demand and connect new generation facilities and, depending on the scenario, could vary by a factor of two in the long term

For the first time, the description of the different electricity mix scenarios includes an estimate of the related distribution grid investments, based on analyses conducted by Enedis.

An estimated €61 billion will need to be invested in the grid in the 2021-2035 period to integrate non-dispatchable variable generation, keep up with growing electricity demand and the electrification

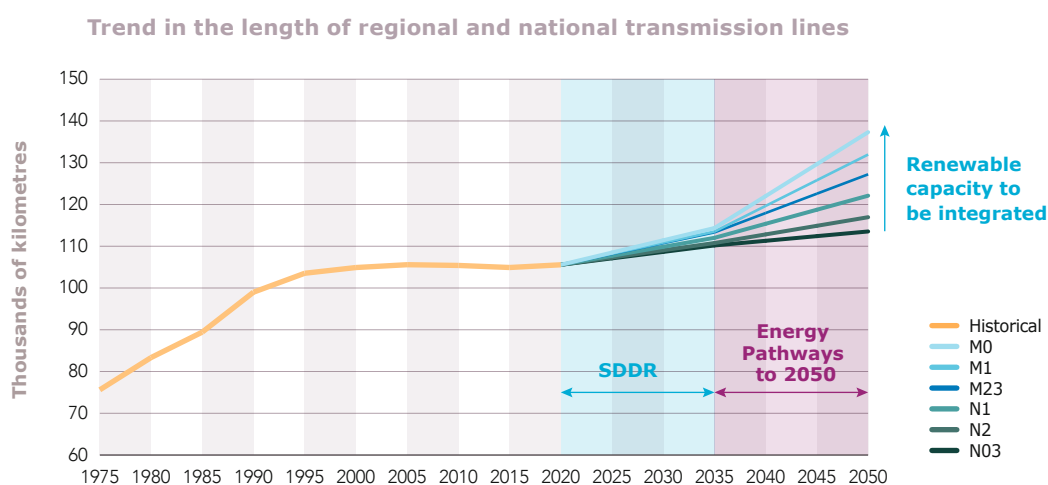
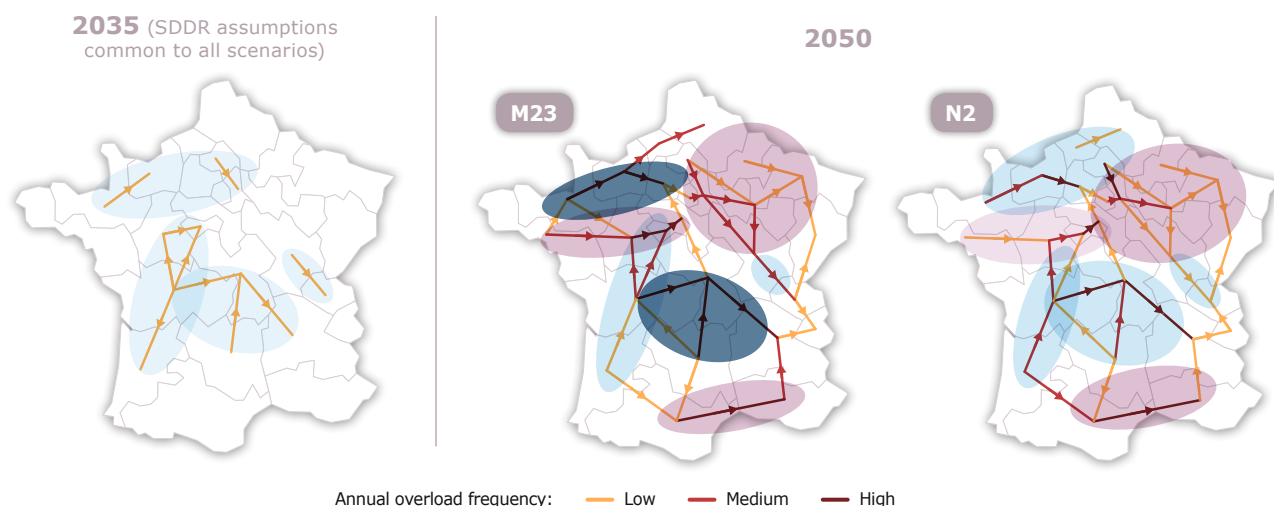
of end-uses, and accommodate new forms of consumption, all while maintaining the same level of reliability. This industrial programme will be national in scope but local in implementation, and planned in concert with the different actors. Enedis will be drafting a network development plan for this undertaking.

Over the longer term, Enedis's trajectories depend largely on the scenario considered. The cost of

adapting the network to consumption trends and new generation sources alone could as much as double, from €2 billion to €4 billion a year on average over the 2020-2050 period, marking an acceleration from past years. Network investment requirements are higher in the scenarios with a high share of renewables, and even greater in scenarios calling for distributed generation sources connected to the low- and medium-voltage grids (notably small solar systems).

Key finding 9 Potential adaptations to the public transmission network under different scenarios

Evolution of the weak points identified in the Ten-Year Network Development Plan (SDDR) in scenarios M23 and N2



The creation of an efficient “low-carbon hydrogen system” will help decarbonise certain sectors that are hard to electrify, and will be necessary for energy storage under scenarios calling for very robust renewable development

The focus on low-carbon hydrogen in the energy debate is recent, but intense. The promise of a “hydrogen revolution” may indeed seem very appealing (a vector that offers flexibility, and can be mass produced from low-carbon electricity and substituted for fossil gas in many end-uses).

Much uncertainty nonetheless remains about the hydrogen economy. This is repeatedly creating confusion about hydrogen’s role as an *energy decarbonisation solution* and as an intermediate storage solution for electricity production needs.

1 Short-term priority: decarbonise existing hydrogen uses and develop new ones in industry and freight transport

Hydrogen is first and foremost a way to decarbonise sectors that are difficult or even impossible to electrify for technical or economic reasons. Therefore, the first priority is to replace the hydrogen produced from fossil fuels (95% gas, oil and coal) currently used in industrial processes in France (in the refining sector, for the production of ammonia or chemicals) with low-carbon hydrogen.

Moreover, low-carbon hydrogen should increasingly be used in heavy mobility, particularly for long-distance road transport.

The “core supply” of low-carbon hydrogen needed to decarbonise these uses is estimated at 35 TWh_{H2}. Producing such quantities will require developing electrolyser capacity, starting with large facilities drawing low-carbon electricity from the power grid and located near industrial areas or refuelling stations.

The related electricity consumption, under the baseline trajectory, is close to 50 TWh_e.

Scenarios calling for much more intensive use of low-carbon hydrogen are currently on the table, notably at the European level. In France, they are included in *Energy Pathways to 2050* under the “Hydrogen +” variant. They imply expanding low-carbon hydrogen supply while at the same time stimulating demand for that energy: ammonia for maritime transport, steel-making, biofuels for aviation. For some of these uses, there is currently no consensus as to the role hydrogen should play relative to direct electrification or the use of agrifuels. Yet the fact remains that in all scenarios calling for increased hydrogen use, additional electricity generation will be necessary, except if imports are relied upon. In a configuration involving massive growth in the use of low-carbon hydrogen produced via electrolysis in France, the quantity of electricity required is much higher, approaching 170 TWh_e.

2 A long-term resource: developing flexible hydrogen storage to prepare for scenarios with high shares of renewable energy

Hydrogen production via electrolysis is considered a flexible solution, one that can adapt to variations in renewable energy generation and total electricity consumption: in other words, it can be a considerable source of flexibility to help balance the power system.

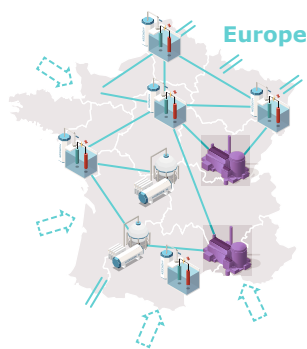
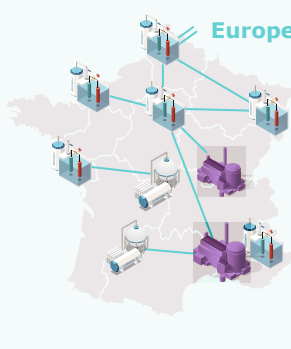
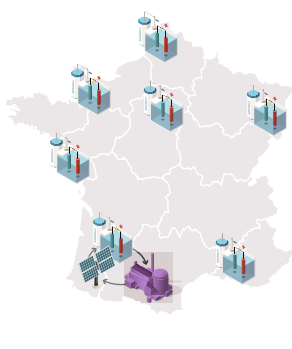
If electrolyzers are connected to a large hydrogen system equipped with storage capacity, their operation can be modulated in greater proportions than many other electricity end-uses: unlike electric vehicles,

which still have limited battery capacity and must be charged regularly, electrolyzers could stop operating for extended periods of time (for instance during weeks when there is no wind) when sufficient electricity reserves are available to produce the hydrogen needed. **However, this flexibility is only possible when hydrogen storage and transport infrastructure is in place, and such availability is not a given today.** The cost of these solutions, currently very uncertain, is factored into estimates here.

Hydrogen is also a crucial energy vector for operating thermal plants in power systems with a high share of renewable energy in the mix: the cost of procuring it thus has a direct impact on the plants' competitiveness. They could become more competitive if hydrogen can be imported from other parts

of the world with good control of prices and supply chains, if production in France relies on large wind or solar farms, or if other decarbonised gases such as biomethane are used as a supplement, within the physical limits set forth in the NLCS.

Key finding 10 Degrees of integration of the "hydrogen system" relative to the power system

	Vision of a hydrogen system that is largely interconnected and very flexible	Baseline: flexible hydrogen system	Vision of a hydrogen system that is not very flexible
Electrolysis	Flexible electrolyzers	Flexible electrolyzers	Non-flexible electrolyzers: continuous operation
Storage & network	- Storage largely accessible at a European level - Robust interconnections + trade routes with the rest of the world to import hydrogen at less cost	- Storage largely accessible (either via interconnections or thanks to its development in France) - Cross-border trading possible to pool storage capacity, but no massive imports	- Very limited storage possibilities - No imports-exports
Thermal generation	Thermal power plants fuelled by hydrogen from the network (produced in France or imported)	- Thermal power plants fuelled mainly by hydrogen from the network - Variant combining synthetic methane and biomethane	Thermal power plants fuelled by locally produced synthetic methane
Cost of gas for electricity generation	About €70/MWhLHV	About €120-130/MWhLHV	About €160/MWhLHV
Schematic map of the network			



Electrolyser



H₂ storage



Thermal power plant



Trade routes for importing decarbonised gas



Interconnections

Scenarios with a very high share of renewables in the mix, or the one calling for the lifetime of existing nuclear reactors to be extended beyond 60 years, imply overcoming major technological challenges for carbon neutrality to be reached in 2050

Creating a carbon-neutral system by 2050 represents a technological challenge. Many innovations are anticipated, and their degree of necessity will vary under the different scenarios: electric vehicles using batteries made with less rare metals, the power-to-gas-to-power loop via hydrogen or synthetic methane, thermal power plants running on decarbonised gas, digital technologies for demand-side management, small modular reactors, new marine energies such as tidal turbines, etc.

The IEA recently estimated that nearly half the emissions reductions needed to reach carbon neutrality in 2050 rely on technologies that are still in the demonstration or prototype phase. In its analysis, RTE sought to minimise reliance on not-yet-established technologies, instead favouring ones that are industrially mature. That being said, each scenario does require meeting a certain number of technical prerequisites.

From a technical standpoint, **the analysis shows that no fundamental distinction can be drawn between the M and N scenarios.** They all ultimately lead to a high share of renewables in the mix and will thus require tackling the issues that arise when non-dispatchable sources make up the bulk of the generation fleet, albeit to different degrees.

While it would appear that the related technological and R&D challenges could be “overcome” over the coming decades, the “100% renewable” scenarios and those that involve extending the lifetime of existing nuclear reactors beyond 60 years require that a large number of critical technical prerequisites be met in the near term. As it stands, there is no guarantee that will happen. This means that if a decision is made about one of these scenarios today, or the principle of developing a more technologically diverse electricity mix is ruled out, it creates a risk that carbon neutrality will not be achieved in 2050.

1

The technological prerequisites for scenarios with a high share of renewables in the mix were described in the joint report published by RTE and the IEA in January 2021

The four prerequisites described are as follows: (1) maturity of the technological solutions that can maintain the stability of the power system with no conventional generation, (2) the large-scale deployment of flexibilities, (3) control of issues around developing technical reserves, and (4) upgrading of national electric grids.

The technical validations that must be completed for this target to be met remain significant, and will require substantial and sustained R&D.

All the “M scenarios” are subject to these four conditions being met, but so is N1 since the share of renewables would exceed 80% in 2060.

2

Maintaining nuclear capacity of about 50 GW also poses technological challenges

Five of the six *Energy Pathways to 2050* scenarios assume that certain existing nuclear reactors will be kept in service beyond 50 years, subject to meeting safety requirements that would be systematically verified ahead of time. France’s nuclear safety authority ASN has indicated that extending these reactors’ lifetime beyond 40 years, which it has approved, would already require “an exceptional amount of work.”

Three of the six scenarios call for the construction of new EPR 2-type reactors, which poses an industrial challenge. **The N03 scenario implies going even further, meeting four conditions:** (1) successfully extend the lifetime of most reactors to 60 years, (2) keep some in operation beyond 60 years (especially if others are shut down at 50 years), (3) build and commission 14 EPR 2-type reactors (i.e. eight more

than in the “New Nuclear France” programme), and (4) deploy 4 GW of SMR capacity. **Such a scenario would require establishing early on the feasibility of extending lifetime beyond 60 years.**

Generally speaking, it would take a global R&D effort in the nuclear industry, from the design of new reactors through to the technologies that make it possible to “close the cycle.”

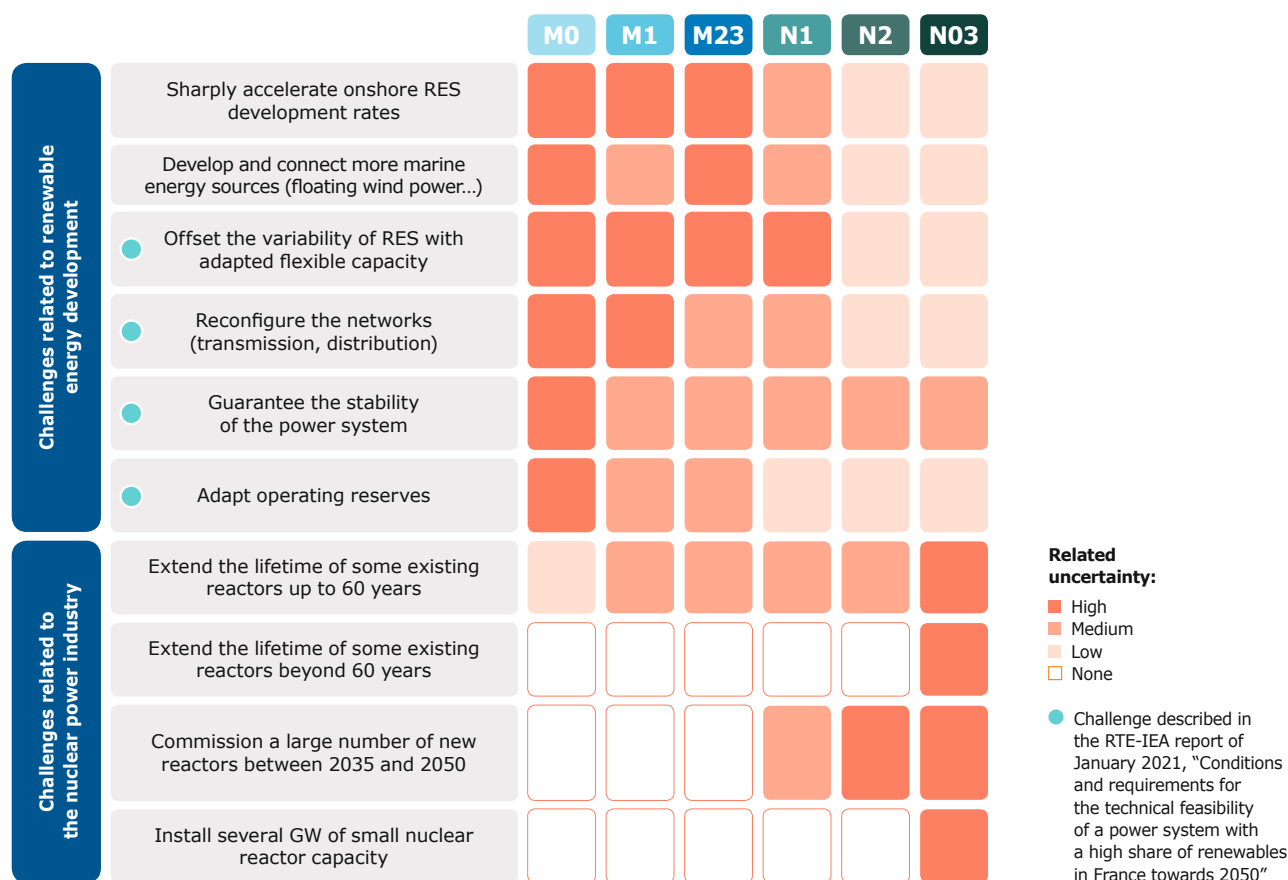
3 A scenario maintaining significant nuclear generation capacity together with robust renewables development naturally limits the risk of missing climate goals

Scenarios like N2 make it possible to overcome several technical and industrial challenges and achieve a high level of low-carbon electricity generation.

Indeed, dependence on the hydrogen system is lesser in this scenario, upgrades to the network are in line with the acceleration already planned for 2035, and issues around maintaining synchronisation are less significant. On the nuclear side, this type of scenario is not dependent on the extension

of the lifetime of reactors beyond 60 years, and its trajectory is compatible with a staggering of the closure of existing reactors in order to prevent a “cliff effect.” The creation of an industry around SMRs, which are not yet developed in France industrially, becomes an opportunity (to reduce the rate at which EPR 2s must be built) rather than an obligation. Building 14 EPR 2 reactors in 30 years nonetheless represents an industrial challenge that should not be underestimated.

Key finding 11 Technological and industrial prerequisites associated with the different scenarios and uncertainties



Starting now, the transformation of the power system must take into account the likely consequences of climate change, particularly its effects on water resources, heat waves and wind patterns

The French power system is already sensitive to weather patterns: electric heating contributes to peak demand periods during cold spells, water reserves at hydro dams depend on rainfall, and some nuclear power plants may be unavailable during heat waves or droughts.

Over the longer term, changes in the electricity mix and the climate will make it even more important to

prepare for extreme weather phenomena, for two reasons:

- ▶ climate change will make it necessary to further adapt the system to resist the effects of warming;
- ▶ the development of variable renewables will make the system more sensitive to weather phenomena. The issue of periods with no wind becomes a decisive factor in the analysis of flexibility needs.

1 Climate change will alter consumption and generation profiles: its consequences must be factored into the scaling and adaptation of the power system

In the report it published in August of 2021, the IPCC warned that climate change will inevitably continue over the coming decades, and it invited all economic actors to prepare to adapt their infrastructure accordingly. This is particularly applicable to power system infrastructure, the security of which is vital to the country.

When it comes to managing the power system, the most visible effects of climate change are temperatures: according to the 2020 DRIAS report by French weather service Météo-France, the average rise in temperatures in France could reach between +0.8°C and +2.9°C in the 2041-2070 period relative to 1976-2005. The intensity and frequency of cold spells will decrease (though the risk will not disappear), while that of heat waves will increase: by 2050, one in three summers could see a heat wave similar to the one recorded in 2003. These changes in temperature will drive up the use of electricity for air conditioning, which will be largely offset on a yearly basis by a decrease in consumption for heating.

Beyond these effects on consumption profiles, climate change will have a significant impact on electricity generation and transmission infrastructure. **Water reserves will need to be managed differently** since snowmelt will fill up dam reservoirs earlier in the year, and droughts will extend into the early autumn more frequently. **Existing nuclear power plants located along rivers will be affected by periods of intense heat and drought more often:** though the amount of energy “lost” will remain low at an annual scale, temporary shortfalls may be considerable. The sensitivity of new nuclear reactors to these weather changes could be minimised **through siting choices (giving priority to locations near the sea or rivers with low constraints in terms of flows and threshold temperature) and thanks to the cooling towers that will be required with future plants near rivers.**

Lastly, the sizing of the power grid will need to evolve to take into account the transmission capacity of overhead lines affected by rising temperatures.

2 These changes in the mix will make the power system more sensitive to wind conditions rather than primarily to temperatures, as is the case today

In 2050, the electricity supply-demand balance will be affected by weather conditions in new ways.

First and foremost, the development of wind and solar power will make the power system balance much more sensitive to wind patterns and sunlight, and less sensitive to temperatures.

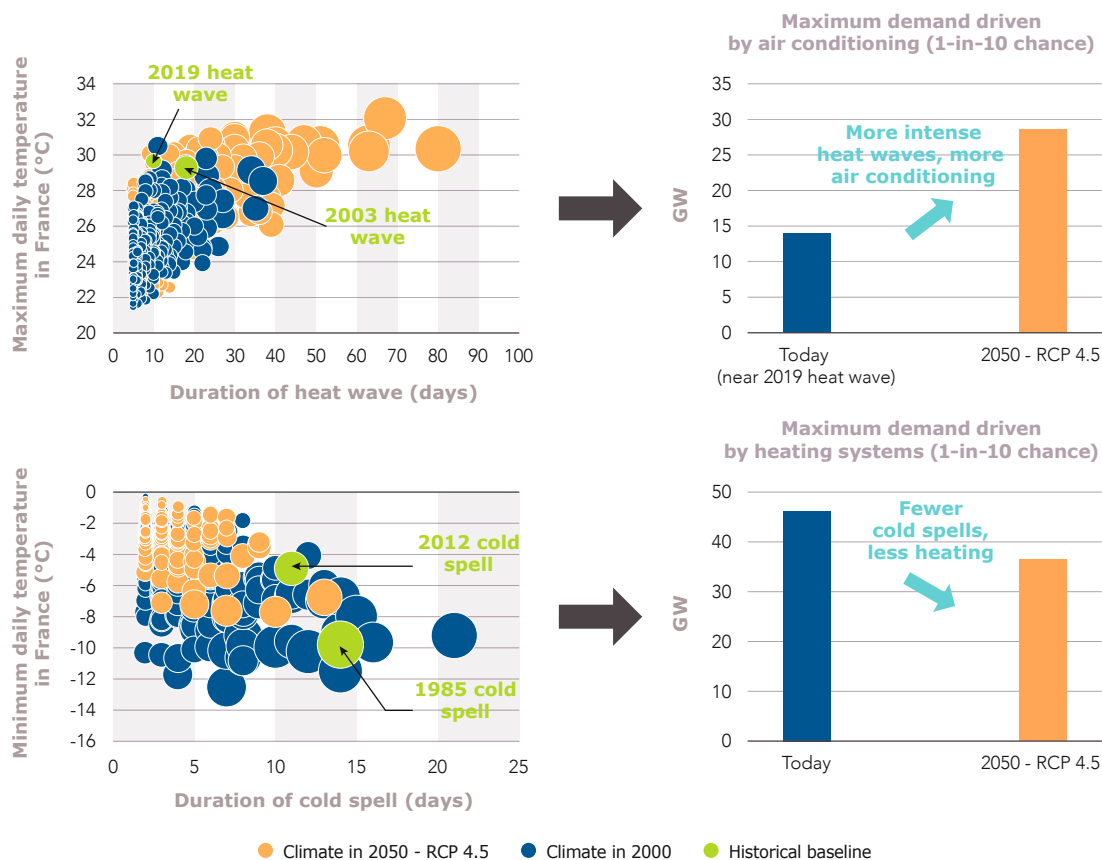
As of today, cold spells in winter pose the biggest threat to security of electricity supply. Over the coming decades, the nature of this risk will evolve with supply tension observed mainly during periods when temperatures are low and there is no wind (in the past, the risk was concentrated mainly during periods of extreme cold).

Periods of cold weather with no wind are the subject of much debate as the future of the electricity mix is considered, as they will create the need for very significant dispatchable capacity under scenarios with a high share of renewables (several tens of gigawatts). It will not be possible to address this type of situation without such capacity.

More frequent drought periods stretching from late summer into autumn will also create tension in balancing electricity supply and demand, especially if they coincide with periods with little wind. Here again, dispatchable capacity will be necessary, and it is factored into the analysis of the different scenarios.

Key finding 12

Trend in the frequency of extreme climate events (heat waves and cold spells) between now and 2050 (IPCC's RCP4.5 trajectory) and impact on power demand for air conditioning and heating



Renewable energy development raises concerns about the use of land and the limitation of other uses. Its growth should be able to accelerate without putting excessive pressure on soil artificialisation, though care must be taken to preserve living environments in each region

1 Acceptance of wind and solar power depends more on their integration into local landscapes than on environmental considerations

The French power system was built around nuclear power plants, large hydro dams, and a few thermal power plants. Generation is highly concentrated within a few parts of France, where related infrastructure tends to be readily accepted given the jobs and local tax revenue it creates.

Meanwhile, the “fossil system,” which supplies more than 60% of the energy consumed in France, is not very visible: oil and gas fields are located in other countries, while the few refining facilities in France are concentrated in port zones that tend to be industrialised areas, and the gas pipeline network is underground...

As a result, the most visible portion of the French power system is the high- and very high-voltage electric grid.

The renewable energy sources that will be developed to make carbon neutrality possible will be spread out across the country. Consequently, the energy production system that had until now been mostly invisible, since infrastructure was located outside France or was extremely concentrated, will become more visible.

This “emergence” of visible infrastructure is the subject of most of the controversy surrounding wind turbines and large solar farms and their acceptability to people in France.

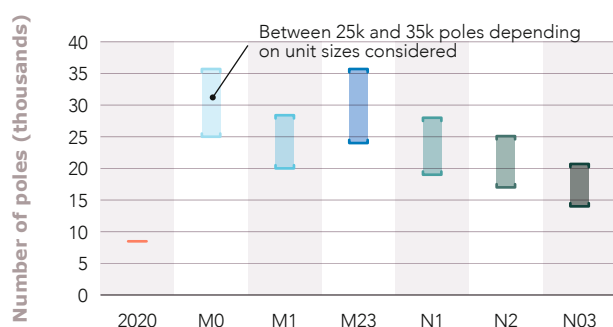
In a word, this issue is first and foremost about aesthetics and heritage.

The analyses in *Energy Pathways to 2050* confirm that infrastructure will become more visible: wind turbines could represent between 14,000 and 35,000 poles, and solar panels could cover between 0.1% and 0.3% of the country.

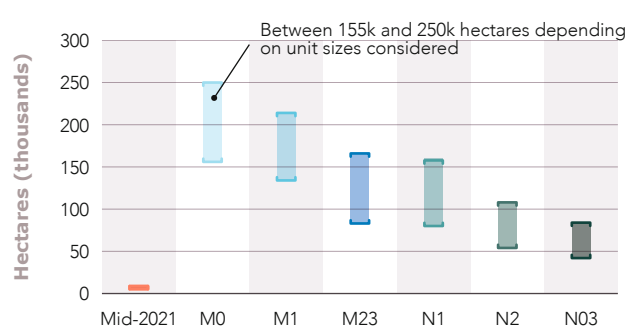
Scenarios that include the construction of new nuclear reactors would result in less space being taken up since these reactors would, in theory, be located on or next to existing sites. **However, this argument around land use should not overshadow the acceptability issues that will necessarily arise around new nuclear facilities, particularly with the focus that would be placed on accident risk.**

Key finding 13 Number of wind turbine poles in mainland France and surface area covered by solar panels

Estimated number of onshore wind turbine poles that will be in place in 2050



Estimated number of hectares covered by ground-mounted solar panels in 2050



2 Generally speaking, renewable energy development does not result in extensive soil sealing or artificialisation

The higher the share of renewables in a scenario, the more land area is used for energy infrastructure. However, soil sealing and artificialisation, the subject of most of the concerns about biodiversity, would remain very low on a national scale. By 2050, the artificialised surface area dedicated to the power system will represent between 20,000 and 30,000 hectares. By comparison, France's highway system alone covers more than a million hectares.

Artificialisation trends are greater in the M scenarios, though the surface areas in question are small relative to corresponding growth in housing, commercial zones and roads (1 to 3%). **Any action that would help limit artificialisation resulting from additional electricity infrastructure (reuse of abandoned wasteland) will help achieve the "net zero artificialisation" goal.**

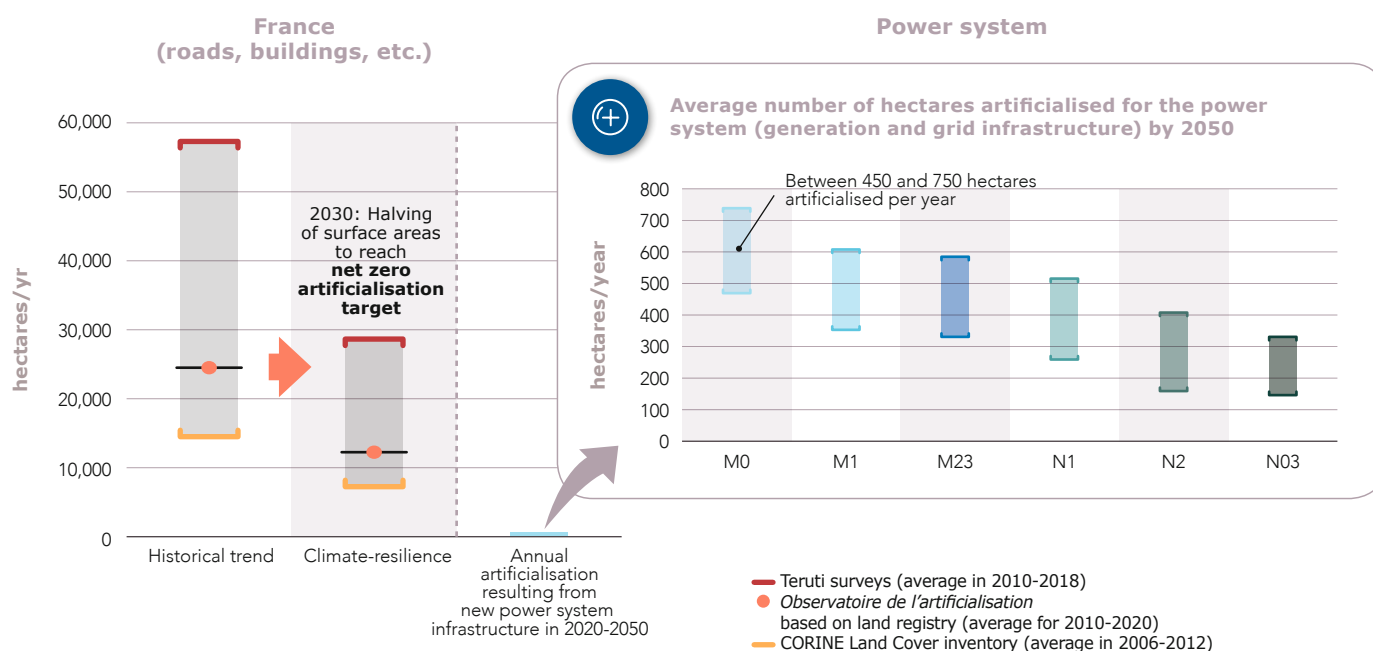
3 The land used for renewable energy infrastructure is generally accessible for co-uses, though with conditions when it comes to photovoltaic

The possibilities for "co-use of land" around electricity infrastructure are different for different technologies. They are low in intensity but cover an extended surface area for wind power, since many uses, notably agricultural ones, are possible around wind turbines. The opposite is true with solar: less space is occupied in relation to installed capacity, but the potential for co-use is much more limited.

The ability to use space under ground-mounted solar panels may be much more limited, even if the soil is not artificialised or sealed, except in specific agrivoltaic models (pastureland and some crops possible).

The study does not identify any structural problems with land ownership, though tensions may arise in certain regions.

Key finding 13 Projected trend in artificialisation through 2050 in the scenarios across all of France (historical trend and target for 2030)



Source: CEREMA, 2021, "The determinants of the use of space".

Note: Artificialisation volumes vary depending on the valuation method used (land registry, sample surveys).

In accordance with the agreement set forth the climate and resilience act, the surface area under solar panels is counted as artificialised surface area here.

Even factoring in the full carbon footprint of infrastructure over its entire lifecycle, electricity in France will remain largely decarbonised and will make a significant contribution to carbon neutrality by replacing fossil fuel energy

1 Renewables and nuclear have a very favourable carbon footprint, even factoring in their lifecycle

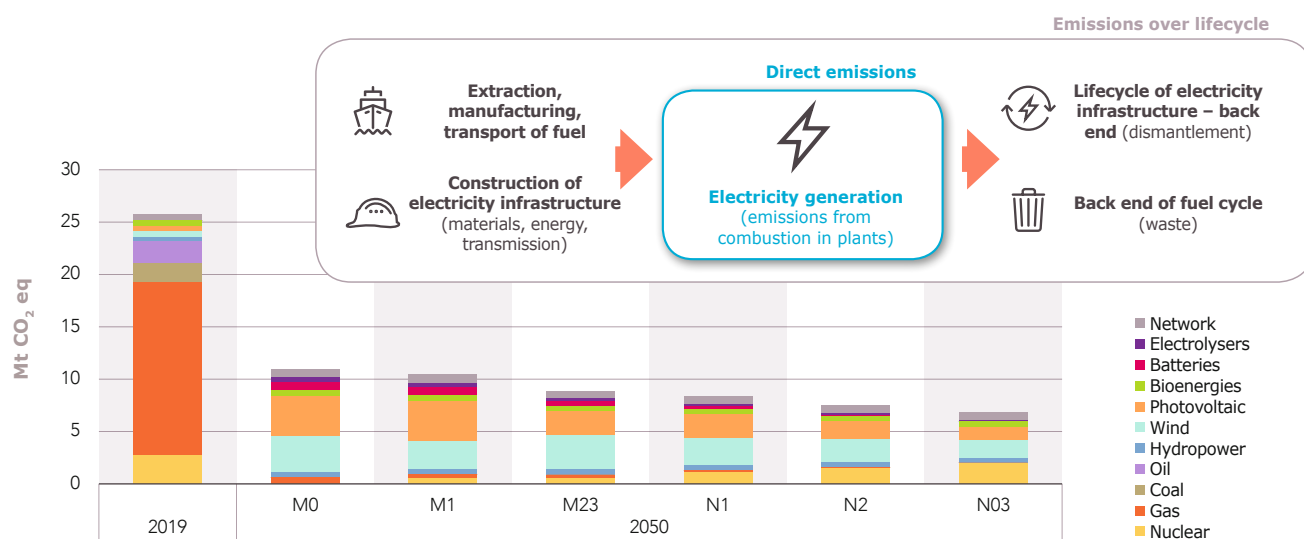
The debate about electricity generation sources is currently focusing both on the greenhouse gases they emit as well as their manufacturing and end-of-life processing.

Today, the lifecycle of materials can be integrated into carbon footprints using a standardised and proven method: **even if the full lifecycle is taken into account, total emissions from renewable and nuclear electricity generation technologies**

are very low, well below those associated with fossil fuels.

Among renewable sources, solar panels have a slightly larger carbon footprint than nuclear or wind power. Yet it is nowhere near that of thermal power plants (reduced by a factor of 10 to 20). This footprint could be further improved if panel production is relocated, notably in the event of a “technology leap” in the type of panels used.

Key finding 14 Greenhouse gas emissions over the lifecycle of the power system



2 Developing more renewable electricity has benefits for the climate even if France's electricity generation is already 93% decarbonised

There is no denying that from an emissions standpoint, the performance of the French electricity mix is very good. Electricity generation in Germany emits seven times more despite rapid growth in the use of renewables as the country has phased out nuclear in

recent years. Emissions are twice as high in the United Kingdom and nearly three times higher in Italy.

This strong starting point may lead some to deny the climate benefits of adding more wind and solar

power in France. **The fact is that continuing to develop wind and solar power will indeed reduce emissions if that capacity is used in addition to existing nuclear:** 1) low-carbon generation must increase to cover the demand currently met by fossil fuels, 2) to increase this potential from the current level, there is no alternative in the short term to developing renewables (the new reactors that France might decide to build would not start producing electricity before 2035 at the soonest), 3) it is necessary to plan more low-carbon generation ahead of the eventual shutdown of existing nuclear

reactors so current performances can be maintained over the long term.

In scenarios in which new nuclear reactors are not built to replace the ones decommissioned, maintaining the same level of climate performance will require that the renewables development timetable be adhered to exactly and that the fossil gas used to power thermal power plants be replaced by green gas starting in 2030-2040. If these conditions are not met, then greenhouse gas emissions from the power system will increase, making it impossible to achieve carbon neutrality.

3 The electrification of end-uses alone would reduce France's emissions by 35% by 2050

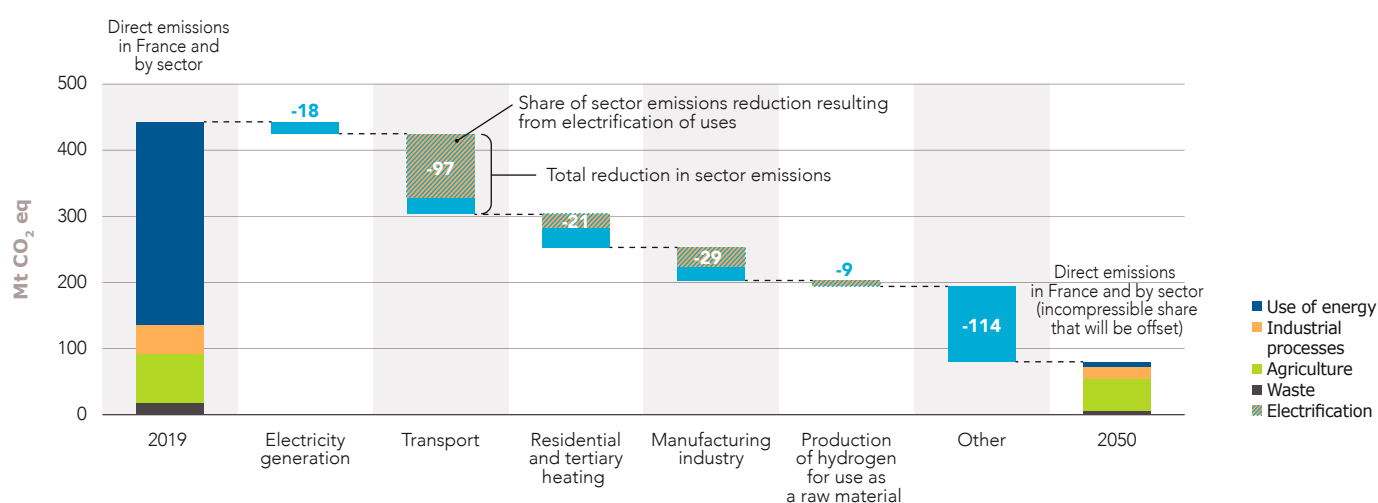
France faces a different challenge than many of its neighbours when it comes to cutting its emissions: while other countries' energy roadmaps have in recent years focused chiefly on developing low-carbon electricity generation, France must now go a step further and decarbonise its entire economy, partly thanks to its low-carbon electricity.

The actions with the strongest climate impact involve replacing petroleum products (petrol or diesel) with electricity (or hydrogen produced from electricity) in passenger vehicles and heavy trucks, and replacing fuel oil and fossil gas heating systems

during building renovation. In industry, greater use of electricity or low-carbon hydrogen for certain processes, or electric boilers, are other ways to reduce emissions.

Overall, the electrification of end-uses can avoid about 150 million tonnes of CO₂ emissions by 2050. Electricity thus has a major role to play, but it will not suffice: the energy mix of 2050 will not be anywhere near all-electric, and the ability to achieve carbon neutrality will also depend on other factors, such as the development of bioenergies and the reduction of emissions from agriculture.

Key finding 14 Trajectory of greenhouse gas emissions and effects of electrification



There may be tension around mineral resource supply in the energy transition economy, particularly for certain metals, and it will be necessary to plan accordingly

1 The energy transition will reduce dependence on fossil fuels but it will also create a need for new mineral resources and supply chains for them

During the 20th century, the recurring themes of energy supply debates related to the size of gas and oil reserves, when peak oil would occur, and issues around dependence on producing countries.

The energy transition of the 21st century has caused a shift in the debate about resources: as the power system ends its dependence on fossil fuels, it will require significant quantities of mineral resources, creating a new set of concerns about supply and dependence. This situation must nonetheless be analysed cautiously, looking beyond superficial arguments.

None of the scenarios points to a major issue with rare earth materials.

Often mentioned during debates about the impact of renewable energy, rare earth materials are in practice little used in power system components (only in certain offshore wind technologies), but are heavily used in other sectors like digital, household appliances, and internal combustion engine vehicles. They are not scarce from a geological standpoint.

However, many resources that will be necessary to the energy transition (copper, lithium, cobalt...) present real criticality issues, which may be of different types and specific to each resource: known reserve volumes, monopolies, conflicts of use and economic importance, substitutability, environmental impacts related to mining, etc.

2 Increasing demand for specific metals for batteries, notably for electric vehicles, must be watched closely

Lithium-ion batteries, the cost of which has decreased sharply in recent years, emerge as a cornerstone of decarbonisation plans. Under the different scenarios, it may be necessary to have batteries dedicated to the power system to support the development of photovoltaic (100 GWh in the highest scenario), but the volumes in question are nowhere near those the development of electric vehicles will involve (about 2,900 GWh for passenger vehicles).

As of today, **the batteries used in vehicles consume metals that are considered critical including cobalt, lithium, nickel and manganese.** These resources raise significant supply issues for different reasons.

Cobalt reserves are limited and its extraction is concentrated in the Democratic Republic of the Congo, while China has a sort of monopoly on its refining. Lithium supply raises significant concerns due to electric vehicle production ramping up across the globe, concerns about growing dependence on China, and limited recycling possibilities.

Specific action aiming to limit the need for these critical resources will be required in all cases: sufficiency in the transport sector (reduction in the number of vehicles), limit on the size of batteries, development of next-generation batteries that use less metals like cobalt, etc.

3 Materials like copper must also be monitored, especially in scenarios with a high share of renewables in the mix

Copper is used in almost all power system components (nuclear and renewables, batteries, grids) as well as in other strategic economic sectors (buildings, transport, telecommunications, industry, etc.) that are expanding across the globe. Tension can be expected on the supply chain, as current mining capacity is probably not sufficient to keep up with a sharp increase in consumption. Demand for copper is higher in scenarios with a high share of

renewables in the mix, but issues of criticality will depend in large part on global supply and demand trends and changes in recycling capacity.

Silicon is also the focus of much attention. While mines are fairly abundant and distributed across the world, it will be necessary to develop new silica mining and production capacity to support solar power growth and to prevent a total monopoly on that type of production.

4 Scenarios involving a nuclear revival require adjusting the long-term strategy for the back-end of the cycle to sustainably manage additional radioactive materials and waste

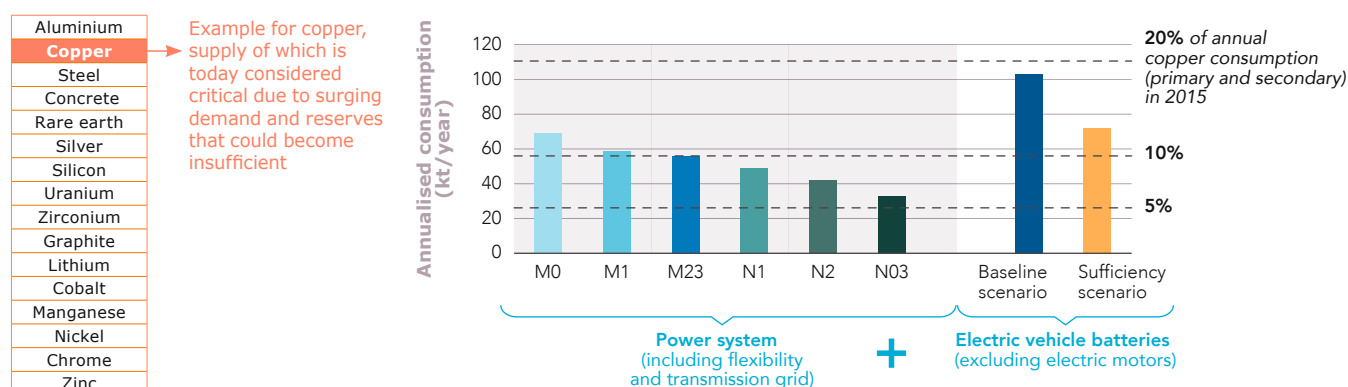
Natural uranium reserves appear to be largely sufficient today to guarantee supply to French nuclear power plants for many decades, including in the event of a robust nuclear revival.

On the other hand, after its use in nuclear power plants, uranium generates different types of substances that must be managed over very long periods given their radioactive nature and life. Some materials may be recycled for use in existing or future reactors: France's "closed cycle" strategy encourages the maximum reuse of these materials, though uncertainty remains about these plans now that experimental Generation IV reactor projects have been suspended in France.

The fuel cycle requires dedicated storage infrastructure (pools) for fuel loading and unloading, and for the processing and recycling of spent fuel. These costs are factored into the economic analyses here.

Nuclear power generation also produces radioactive waste that needs to be stored for tens of thousands of years, this being the focus of the CIGEO project. **A nuclear revival will require more infrastructure to manage waste from new reactors over the long term. These needs are factored into the corresponding scenarios.**

Key finding 15 Projected annual consumption of copper in 2050 under different scenarios and for electric vehicle batteries



By 2050: it will be possible for France to develop a power system adapted to carbon neutrality while keeping costs under control

1 The total cost (per MWh) of France's power system may go up, but the magnitude of the increase can be kept in check (about 15% excluding inflation as a median forecast)

While steep investments will need to be made in the different components of the power system, the study shows that the rising cost of the national power system can be kept in check over the medium and long terms. Within 40 years, the cost per MWh could rise by about 15%, based on the median forecast (excluding inflation): some scenarios and financing configurations may result in the cost being virtually flat, while others point to a greater increase.

The main factor driving up the average cost of electricity generation is the closure of existing nuclear power plants, which are fully depreciated and still competitive even taking into account the cost of the "Grand Carénage" refit programme. That being said, a strategy involving the mass development of renewables with a focus on large farms to take advantage of economies of scale, or a new nuclear programme meeting the cost targets set based on the audits, will make it possible to keep production costs under control provided that financing terms are favourable (especially as a portion of the costliest investments has already been made for the reference units, both in the renewables and nuclear sectors). Between the low and high estimates for long-term power system costs, it is primarily flexibility and network costs that make the difference.

The projected increase is not as steep as what could have been anticipated: building a low-carbon power system that is largely upgraded and scaled up to support the elimination of fossil fuels can thus be accomplished at a reasonable cost, provided that financing costs are low: the central assumption applied in the study is 4%.

On the other hand, an increase of 15% would create a "supply shock" that must be factored into macro-economic forecasts, especially as many of the costs associated with the transition arise downstream. The fact is that reindustrialisation plans should not be made based on the promise that electricity costs will be flat over the long term.

As regards the downstream segment, it currently costs more to build an electric vehicle than one with an internal combustion engine, though once the vehicle is purchased, it is cheaper to power it with electricity than petrol. The same is true of the building sector: there is a cost to a heat pump, but once installed it is inexpensive to use. In industry, it takes money to build new factories, but they use less electricity. The cost of the transition can be lowered if it corresponds to the next cycle of investment in and modernisation of France's production apparatus, which has fallen behind that of its competitors in recent years.

2 If carbon neutrality is to be achieved, the pace of investment in the power system must double

While it will be possible to keep the cost of the over-all power system in check, very robust investment will be required under all scenarios: over 40 years, investment needs to meet electricity demand in France will range between €750 billion and €1 trillion depending on the scenario considered, i.e. between €20 and 25 billion a year.

This implies doubling annual investment totals from today. All power system components are covered by this statement: electricity generation, flexibility resources (electrolysers, hydrogen networks and reserves, thermal power plants, batteries, demand response systems), and transmission and distribution networks.

These investments are significant, but will create a system with very low operating costs, and which will no longer run on fossil fuels.

This is true of France's power system today: it runs primarily on nuclear and renewables, with prices

fluctuating mainly in line with conditions in the European power market via interconnections.

Going forward, the same characteristics will apply to a larger share of energy supply in France.

3 In a carbon neutrality scenario, energy costs are more stable and no longer dependent on the price of fossil gas and oil

Compared to when energy supply is dependent on fossil fuels, the cost of the power system is more stable.

It is determined by parameters some of which can be controlled: most of the industrial chain for nuclear power is located in France, the main components of offshore wind turbines are made in France (blades, nacelles, electric substations) or Europe (cables), and European states are developing a hydrogen strategy to control the key components (electrolysers, downstream logistics). For solar, most of the

supply chain is extra-European, though there could be partial relocation opportunities. As for batteries, significant investments have been announced within the framework of European initiatives and the national recovery plans "France relance" and "France 2030".

The potential sticking points relate to mineral resource supply chains, and they must be planned for when it comes to renewable energies and especially batteries. As for nuclear, costs are relatively insensitive to fluctuations in the uranium price.

4 Keeping power system costs in check requires robust government action to reduce the cost of financing new low-carbon generation and network resources

Controlling the full cost of the power system depends directly and essentially on financing terms for investments. Indeed, studies show that a three-point rise in the cost of capital drives the overall cost up by €20 billion a year over the long term (+30%), while a decrease drives it down by €15 billion a year. This same observation applies to a large number of the actions that will be necessary to achieve a low-carbon society: initial investments are high, and the financing thereof thus shapes the outcome of a low-carbon policy.

Until now, renewable energy sources have been developed in Europe with the help of government support that guaranteed fixed prices for the entire time the facilities remained in operation, allowing project owners to secure favourable financing terms, which in turn drove costs down. The economic projections in *Energy Pathways to 2050* show **there is little likelihood that renewables will be financed directly by market revenues without any public aid or long-term contracts such as Power Purchase Agreements (PPAs).** In other words, even if solar

generation is very competitive, the revenue it can earn on markets could be lower than anticipated due to a cannibalisation effect (market prices plummet when solar generation is at its highest).

The same can be said of nuclear. **New reactors** represent extremely capital-intensive investments, and the experiences of recent years show that **it will not be possible to develop them without robust government support, whether in the form of contracts for difference or direct public investment.** They can be economically attractive as long as financing terms are consistent with those available to other low-carbon technologies.

All public policies that de-risk investment in low-carbon technologies thus have a direct influence on system costs and therefore on the long-term reduction of consumers' electric bills. **Today's macro-economic climate, characterised by both low interest rates and high fossil fuel prices, is particularly conducive to a policy favouring investment in low-carbon energies.**

5 Going forward, energy bills in France will depend less and less on hydrocarbon prices, and more and more on the competitiveness of the power system

Phasing out fossil fuels will have significant consequences at many levels, and they are probably still being underestimated. For households, it will change the structure of energy spending, since a portion of their unavoidable expenses is currently influenced directly by fossil fuel prices (fuel for mobility, fuel oil or fossil gas for heating).

Preliminary analyses, which will need to be consolidated in the next phase, were conducted for Energy Pathways to 2050. They show that the energy transition will not result in significantly higher costs than with a fossil fuel system, and that in some cases it will create opportunities to stabilise and even reduce core energy expenses.

Energy spending varies widely from one household and company to the next. The comparison between a system running on fossil fuels and one based more broadly on electricity depends more on hydrocarbon prices on the market, which swing considerably over time, than on power system costs. Relative to periods when fossil fuels are abundant and cheap, a switch to low-carbon electricity will drive costs up. On the other hand, relative to situations of oil price tension, which have become much more frequent over the past 15 years, **the transition to a low-carbon power system can result in considerable savings for some types of household, even factoring in the cost of the *Energy Pathways to 2050* scenarios.**

6 If the moderate costs associated with the French power system are to be reflected directly in energy bills, redistribution mechanisms must remain in place

France's power system is already decarbonised and competitive. This value is returned to French consumers through "off-market" mechanisms. Residential electricity prices in France are among the lowest in Western Europe (only Sweden, which has the same type of mix combining renewables and nuclear, does better).

That said, in a highly interconnected system, the market electricity price depends on how supply and demand are matched up in different parts of Europe. In other words, it reflects tensions on hydrocarbon prices and the CO₂ allowance price (EU-ETS market). The fact that electricity prices can be affected, even in France, by the consequences of the recent

surge in gas prices and the geopolitical tensions affecting supply, even though France relies little on gas for electricity production, underscores just how interconnected the power system is today.

For French consumers to continue to see the economic benefits of France's generation mix reflected in their electric bills over time, it will be necessary to maintain ad hoc regulatory systems over the long term. Indeed, the different scenarios RTE analysed suggest that relatively stable production costs in France will coexist with highly variable electricity prices in the interconnected European system over the long term, to varying degrees in different scenarios.

By 2030: developing renewable energy sources as quickly as possible, and extending the lifetime of existing nuclear reactors in order to maximise low-carbon generation, will increase the chances of meeting the “-55% net” target set in the new European package

The IPCC report of 9 August 2021 once again stressed how important the next decade will be for climate action. Countries must take advantage of the COP 26 meeting in Glasgow in November to adopt new targets that will keep temperature rises within the limits set forth in the Paris Agreement.

As of today, France is committed to reducing its emissions by 40% by 2030. Numerous reports, notably those published by France’s High Council on

Climate (*Haut Conseil pour le climat* – HCC), show that, based on current measures, this target will be difficult to meet, and that a very large number of levers will need to be activated for that to happen.

And yet the target will be raised under the new European Green Deal, which calls for a net 55% reduction in emissions by 2030. The challenge that lies ahead is thus enormous.

1 It is possible to step up efforts to meet the new target for 2030 if all potential levers are activated

All analyses in the *Energy Pathways to 2050* study show that a strategy combining (i) the development of new electricity uses, (ii) a strong focus on energy efficiency (even energy sufficiency), and (iii) maximised production of low-carbon electricity, will significantly speed up large-scale decarbonisation in France.

An acceleration of the fossil fuel phase-out is considered in the “Acceleration 2030” variant of the report. It implies rapidly changing the pace of switching to electricity in the three biggest greenhouse gas-emitting sectors in France: transport, industry and

buildings. The variant lifts electricity consumption to 546 TWh in 2030 (versus 508 in the baseline trajectory). Increased energy sufficiency could drive that value down, while a failure to reach the efficiency targets set forth in the NLCS would cause it to rise.

This trajectory is compatible with a scenario in which diesel and petrol internal combustion vehicles are no longer sold after 2035, with an aggressive policy of phasing out fuel oil in residential heating and switching from gas to heat pumps, and with significant reinvestment in industrial production capacity.

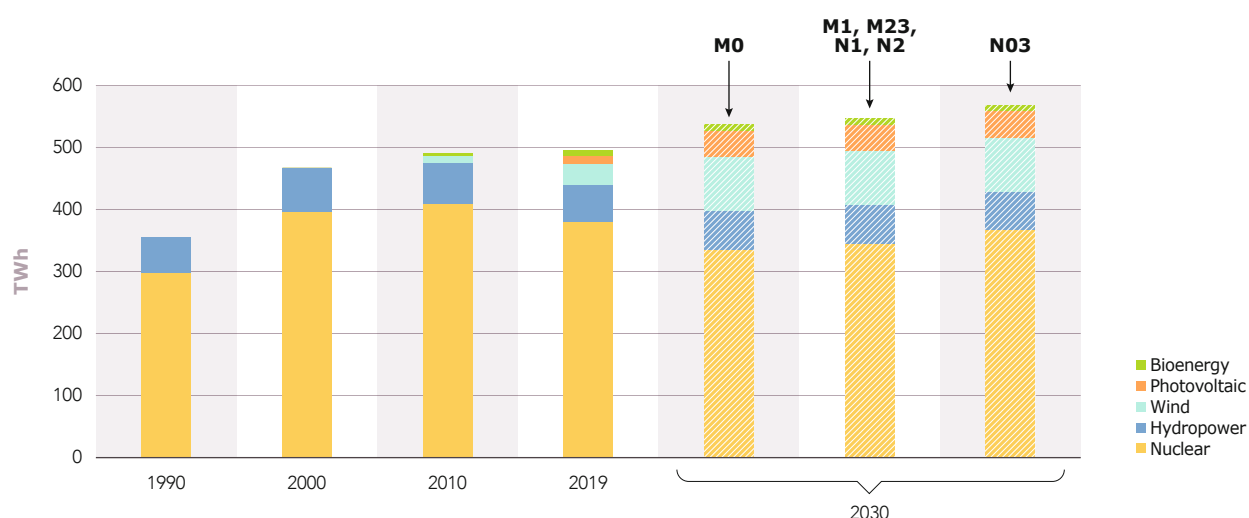
2 This trajectory implies maximising low-carbon electricity production

An approach involving boosting low-carbon electricity generation capacity (additive approach, “renewables + nuclear”) presents the best climate outcome in the short/medium term, and is thus the likeliest one to allow the climate targets for 2030 to be met.

Conversely, the scenarios calling for quickly replacing nuclear with renewables reduce the decarbonised generation potential. This means they cannot support a strategy of acceleration by 2030, and are only compatible with an objective of keeping emissions at their current level if two conditions are met: a very

robust pace of renewable development and the activation of sufficiency (not just efficiency) levers.

Implementing such an approach requires simultaneously accelerating the pace of development of renewables to their maximum level, and keeping reactors in service for longer by making adjustments to the shutdown timetable included in the Multiyear Energy Plan, without prejudice to the need for all reactors to meet safety requirements set by the ASN. Such a modification of the timetable would nonetheless need to be consistent with the long-term strategy for managing the resulting “cliff

Key finding 17 Production of low-carbon electricity in France (historical trend and projections for 2030)


effect” associated with the age pyramid of the fleet (large number of reactors reaching the end of their lifetime at the same time), which requires that shut-downs be staggered over a long period. If the goal is to strengthen the climate targets for 2030, then **the options to be debated in preparing the future**

Multiyear Energy Plan could focus on sticking to and even accelerating the renewable energy development trajectory on the one hand and the staggering of the nuclear reactor shut-down trajectory on the other, all while keeping up efforts on the energy conservation front.

3 An additive approach to low-carbon electricity production is a very competitive option for decarbonising

The strategy of addition is virtuous from an emissions standpoint, and economic assessments underscore its benefits.

The cost of extending the lifetime of reactors, factoring in the cost of the “Grand Carénage” nuclear plant refit programme, can be estimated at between €30 and €40/MWh: in other words, keeping existing reactors in operation will be very profitable. Sensitivity analyses show that this would be the case even if the work required on the plants turned out to take longer or cost more than anticipated. The risks associated with the fourth ten-year inspections thus do not relate to power system costs, but rather to security of supply if the plants are unavailable for a long period due to the scope of work (though the first set of fourth ten-year inspections went according to schedule, not counting the impact of the health crisis).

From an economic standpoint, RTE’s Generation Adequacy Report for 2017 identified a limit to the potential lifetime extension if there is excess renewable electricity capacity at a European scale (electricity demand flat or declining in the main countries, robust development of renewables, low market prices). This limit is no longer an issue given how the European context has changed: renewable energy development programmes in Europe have generally fallen behind schedule, while nuclear reactor shutdowns are mostly on schedule – putting pressure on the supply of low-carbon electricity –, and the outlook for electricity demand growth points to an increase (especially factoring in hydrogen production).

Renewable energy development also remains very competitive relative to the value of the tonne of CO₂ avoided.

Overall, the policy followed in the Multiyear Energy Plan, which factors in the initial cost of developing and connecting offshore wind turbines, does not drive up system costs substantially. With electricity generation costs at these levels, and more uses being electrified, CO₂ abatement costs range from

0 to €200/tCO₂ for mobility, are close to €100/tCO₂ for replacing fossil fuel boilers with heat pumps, and are in the €150 to €250/tCO₂ range for low-carbon production of hydrogen. These figures are below the value the actions create for the climate over the long term (also known as the shadow price of carbon).

4 The interconnection of the European power system protects France from any risk of stranded costs from an economic or climate standpoint

In an interconnected power system and with neighbouring countries relying heavily or mostly on fossil fuels, France does not run the risk of incurring stranded costs by developing or maintaining its low-carbon generation fleet. Electricity exports are profitable from an economic standpoint, as prices on the European market usually depend on fossil fuel prices and the carbon price on the EU-ETS market.

This decision would also reduce greenhouse gas emissions, but at a European scale. Indeed, should the uptick in electricity demand in France not materialise as quickly as anticipated, the country would export more electricity, as a result of which gas- and coal-fired plants in neighbouring countries would operate even less. Over the coming decade, the resulting CO₂ emissions reductions in Europe would be similar in proportion to the gains achievable in France thanks to the electrification of end-uses.

Whatever the scenario considered, action cannot be delayed

All the key findings outlined here confirm that there are multiple emergencies that require immediate action.

The first is the need to address the climate crisis by putting France on a trajectory that leads to decarbonisation.

While Europe is already on that path, it will have to meet some major milestones going forward: net 55% reduction in emissions by 2030 (relative to 1990) per the target adopted this year by the European Union, with emissions falling further in 2040 before carbon neutrality is achieved in 2050. By that time, France's emissions will need to be only marginal, merely matching its carbon sinks (primarily its forest and crops).

Some of the challenges that need to be addressed fall on the end-use side: it is necessary to gradually transform all sectors of the French economy and activities to end the consumption of fossil fuels, especially oil and gas.

It is true that some of the public policies needed in France are already being implemented and producing results, and that economic tools such as carbon markets are in place at the European level, but trajectories will need to change rapidly to improve the country's carbon footprint. The climate crisis requires moving much more quickly over the next decade than in the previous one, while at the same time ensuring that society is on board with targets and measures, not simply content to transfer emissions to other countries. From this standpoint, *Energy Pathways to 2050* shows that the "extensive reindustrialisation" demand scenario would be beneficial starting in the near term for reducing France's carbon footprint. It should also be noted that ending the country's dependence on fossil fuels, above and beyond any geopolitical or sovereignty issues, would constitute a structural response to the energy crises that have occurred in recent decades, all the way up until today, with the sharp rise in fossil gas and oil prices.

The second emergency, closely tied to the first, has to do with energy efficiency and energy conservation in general.

France will need to go beyond its goal of "emitting less" by switching to less polluting energies like decarbonised electricity, and follow through on its commitment to energy efficiency and "consume less." The stated goal of achieving a 40% reduction in 30 years is ambitious but achievable. In any event, it is necessary to pursue that goal if the country wants to avoid straying from its current trajectories.

The third emergency relates to the transformation of the two decarbonised energy sources that will remain in 2050: bioenergies and electricity.

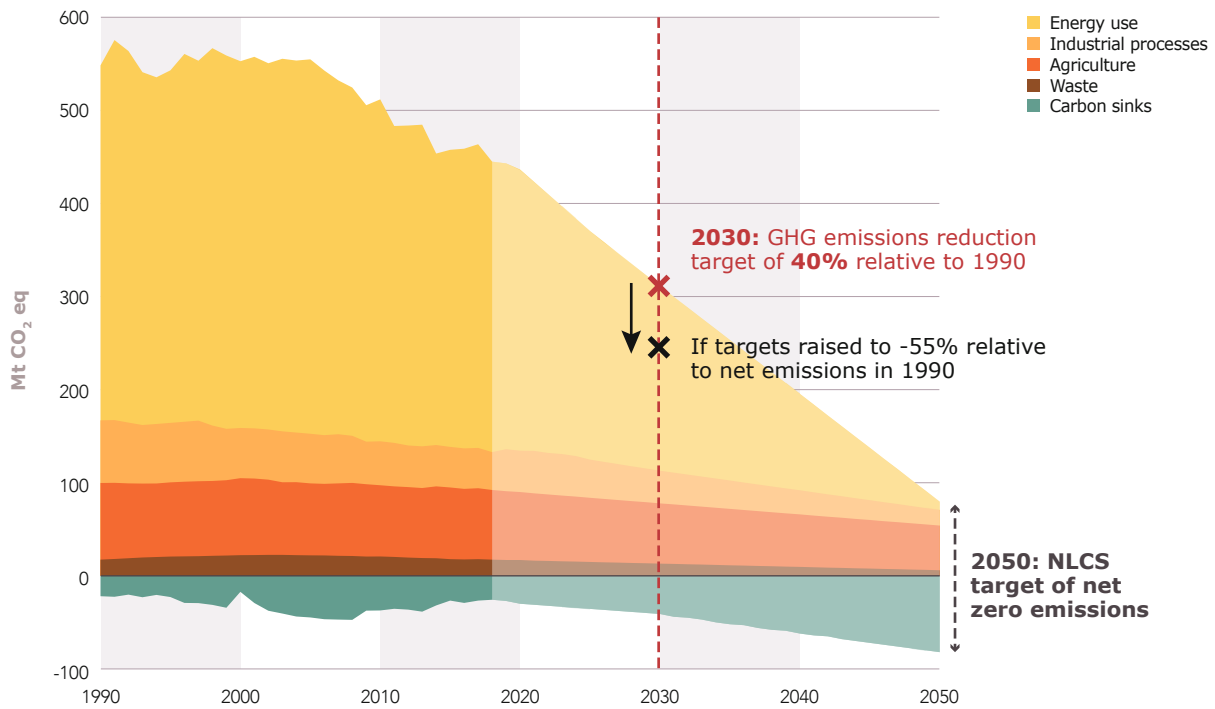
Exploring the power system of the future is the core purpose of the scenarios in *Energy Pathways to 2050*, which outline then compare the possible pathways open to a low-carbon France within the European system. The study reveals a number of industrial emergencies as well.

Under all circumstances, it will be necessary to facilitate and accelerate by all means possible the installation of low-carbon generation resources. Current and estimated timetables for securing authorisations for then building onshore and offshore wind farms, solar farms or new nuclear reactors are very long, such that most facilities planned starting today would only be commissioned after 2030. **Such timetables are not compatible with France's emissions reduction goal, especially if any one of the three key technologies is ruled out.**

These targets are not unrealistic as long as debates about them are conducted in a calm and constructive way. This is the purpose of the *Energy Pathways to 2050* study: to inform the debate and allow public decision-making based on scientific data that is documented, discussed, and transparent.

The full report published on 25 October 2021 outlines the main findings from phase II. It will be supplemented by in-depth analyses of certain variants and scenarios in the first quarter of 2022. RTE recommends that the detailed study of the possible paths forward for the power sector be updated in five years, once guidelines for France's energy-climate strategy have been adopted through the next programme law.

Key finding 18 Trend in greenhouse gas emissions and greenhouse gas sinks (historical trends and targets)



(Source: SNBC/NLCS)



Le réseau
de transport
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RTE
Immeuble WINDOW - 7C Place du Dôme,
92073 PARIS LA DEFENSE CEDEX
www.rte-france.com

