Capgemini invent | FRANCE renouvelables système électrique pilotable

Renewable Power System Observatory

2024

Edition - 1

Op-ed

The gradual and essential transition away from fossil fuels, which still account for over 60% of France's energy consumption, is built on 4 pillars: moderation, energy efficiency, electrification of uses (transport, mobility, residential and tertiary buildings, industrial processes) and the development of renewable and/or low-carbon hydrogen energy generation.

The coordinated mobilization of these four pillars brings about three major transformations for the French electricity system.

The first pillar is concerned with adapting how the electrical system is structured and operated in order to integrate significantly higher shares of renewable energy, and more specifically wind and solar. Indeed, renewable energies, which currently account for about 30% of France's electricity production, will need to exceed 50% by 2050;

The second pillar is driven by a substantial increase in the quantity of electricity produced, transported and distributed, which is expected to rise from approximately 480 TWh today to over than 580 TWh in 10 years (by 2035) and to exceed 700 TWh in 2050. This growth is largely due to rising demand linked to the expansion of electricity usage in passenger and freight transport, buildings and industry;

The third pillar emphasizes the enhancement of the bidirectional nature of the power grid, which has experienced a significant increase in production sites—now exceeding 600,000 compared to only a few thousand fifteen years ago—fueled by the expansion of wind and solar PV power, particularly among individual producers.

Op-ed

In this period of profound transformation of the electrical system, akin to a second electrification of the country, the governance of France Renouvelables wanted to initiate a new observation tool to assess:

- The development dynamics of the sectors that are key to expanding electricity production capacities over the next 15 years, namely solar photovoltaic, offshore wind and onshore wind;
- To highlight the issues tied to the development of production flexibilities, power storage and low-carbon hydrogen, which are key to ensuring the technical and economic efficiency of the energy system's transition towards a greater integration of renewable electricity sources.

This first edition, which is a logical development following the transformation of France Énergie Éolienne into France Renouvelables, comprises five thematic chapters (covering solar PV, power storage, hydrogen, grid flexibility, and wind power) that provide information on:

- The major industrial players in each of the components of the electrical system;
- Market trends, outlining the growth dynamics and challenges—particularly concerning the economic landscape—that each of the components of the current and future electricity system will have to tackle in order to position the electricity system at the forefront of the decline of fossil fuels, which will have to drop from 60 to 40% of our energy consumption by 2035.

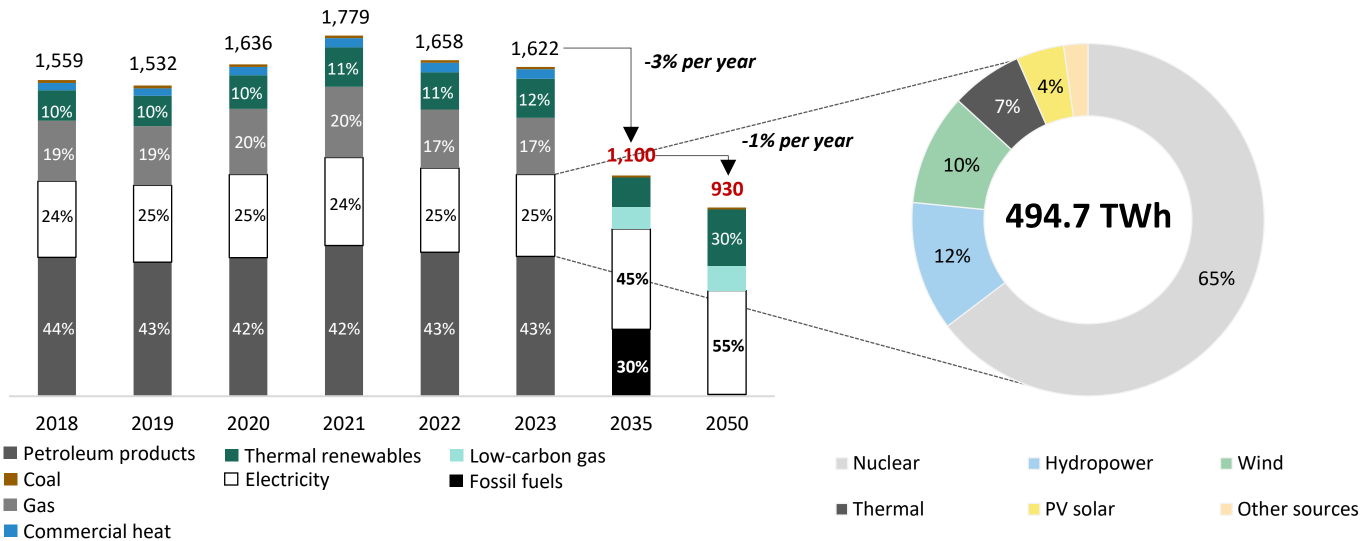
Anne-Catherine de Tourtier – President of France Renouvelables

Executive summary

France's energy pathway must allow fossil fuels to be replaced with renewable electrical sources

Breakdown of final energy consumption in France in TWh

Breakdown of electricity generation in France in 2023



Drivers of decarbonization

- Reduction of final energy consumption through improved energy efficiency and conservation
- Replacement of fossil fuels by renewable and low-carbon hydrogen sources
- Massive end-use electrification, away from fossil fuels

Sources: RTE, Ministry of Ecological Transition, 2035 & 2050: RTE projection scenario A "Successful Acceleration"

A massive electrification of uses by 2035, primarily driven by renewables

+140 TWh (+30%)
in electricity consumption in 2035 compared to 2023*

+190 TWh (+270%)
in renewable electricity generation by 2035 compared to 2023*

+50 TWh (+15%)
in nuclear electricity generation by 2035 compared to 2023*

SOLAR 2023–2035: + 90 GW | 110 TWh

- Accelerating grid-connecting (21 GW pending) through proper planning and implementation of the SDDR
- Tapping the potential of agrivoltaics (which would require only 1% of France's agricultural land) through innovative economic models that share value creation among stakeholders
- Relocating the value chain to Europe in order to secure supplies and costs, while creating jobs and promoting acceptance

WIND 2023–2035: + 57 GW | 150 TWh

Onshore wind:

- Achieving repowering in order to increase capacity on the existing fleet of wind turbines, and bring the industrial production system into alignment with European standards (more powerful wind turbines)
- Strengthening buy-in through citizen consultation and value sharing

Offshore wind:

- Clearly planning future calls for tender to enable all stakeholders in the sector to prepare for the increase in industrial production rates

STORAGE 2023–2030: 6 GW

- Planning capacity development trajectories
- Diversifying revenue streams and making business models more robust
- Developing a European stationary battery industry by leveraging synergies with the use electric batteries for mobility
- Accelerating technological developments aiming to improve battery storage performance and resilience

LOW-CARBON HYDROGEN 2023–2030: +80 TWh

- Securing a stable and low-cost supply of renewable electricity
- Developing storage, transport, and distribution infrastructure interconnected at national and European level
- Achieving successful commissioning, ramp-up and improved dependability of component-manufacturing gigafactories
- Increase the average project size with the aim of achieving a production scale-up

*RTE 2035 Scenario A "high"

Key figures for wind power in 2023

1.3 GW*
in wind power capacity commissioned over the course of the year

50.6 TWh
of electricity generated from wind power

31,447 jobs
(both direct and indirect)

Electricity generation equivalent to the power use of
23 million people

Key figures

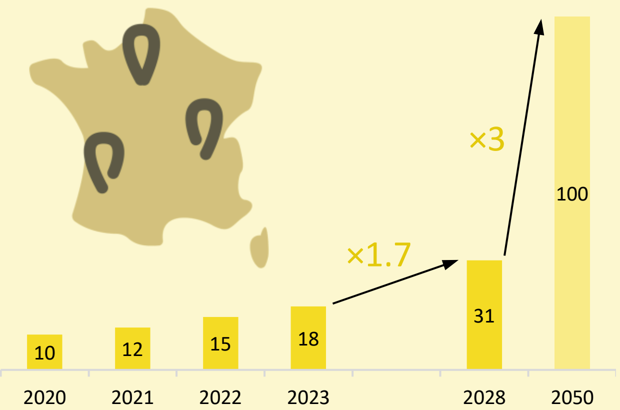
- Over 9,500 wind turbines in France, spread across almost **2,391 sites** (including 7 offshore wind farms) at the end of 2023.
- Wind power is France's **2nd largest source of renewable electricity** after hydropower, and the 3rd largest source of electricity overall.
- France is Europe's **4th largest producer of wind-generated electricity**, accounting for over 10% of the continent's total production.
- Around 124 MW of wind power capacity has been repowered in France in recent years.

Sources: French Ministry of Ecological Transition, Agence ORE, RTE, Engie

* A distinction is made between grid-connected capacity and commissioned capacity. Several tranches of offshore farms (amounting to 0.4GW) were connected to the grid in 2023 but commissioned only in May 2024.

Solar PV, a rapidly expanding sector, presents an opportunity for industrial development in Europe

France’s cumulative solar PV installed capacity (in GW)

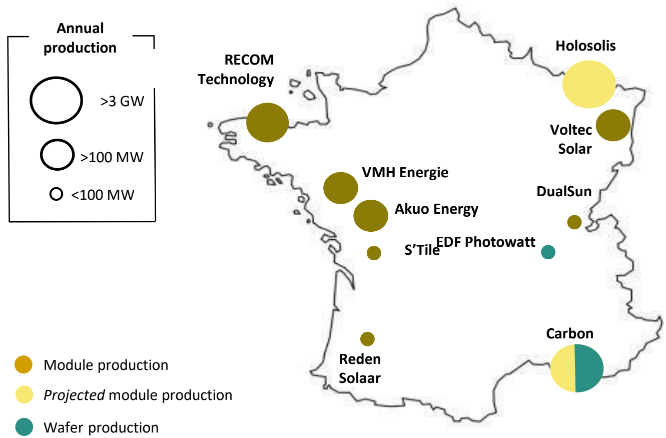


208 GW	750 GW
2022	*2030*

13% Europe’s share of solar PV demand

4% Europe’s market share in the value chain

French reindustrialization is already underway with the establishment of PV module production facilities

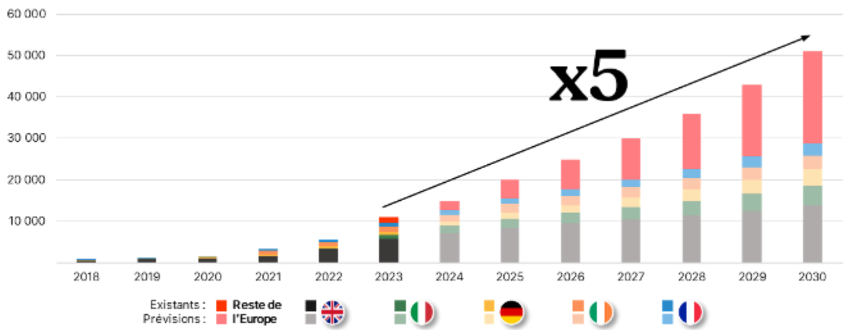


Stationary battery storage is experiencing strong levels of growth that are fostering the development of a European industry

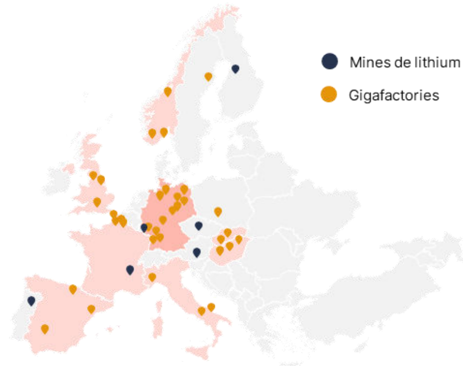
9 GW French objective for 2050 vs. <1 GW in 2023

80% of the market controlled by 6 Asian companies

Projected installed power capacity in Europe (in MW)



Emergence of industrial-scale stationary storage projects in Europe



Improving the flexibility of the electricity network to limit network reinforcement costs and promote the renewable energy integration

High conversion efficiency (90%), which reduces energy losses during storage

A sector of **strategic importance for Europe** with numerous IPCEI projects and a European alliance to build a competitive and sustainable industry

Large-scale industrial projects across France, with the Dunkirk gigafactory and the new lithium mine in Auvergne

Low-carbon hydrogen is a valuable asset for the energy transition

30 MW	6.5 GW	6%	70%	1.5–2 GW
in production capacity in 2023	in production capacity in 2030	share of low-carbon hydrogen in total hydrogen production	of operating capacities are managed by 4 industrial players	average capacity of low-carbon hydrogen projects

With the electrification of end uses, renewable hydrogen plays several crucial roles

Decarbonizing mobility and industry

Hydrogen vehicles emit 3 times less CO2 than internal combustion engine vehicles.

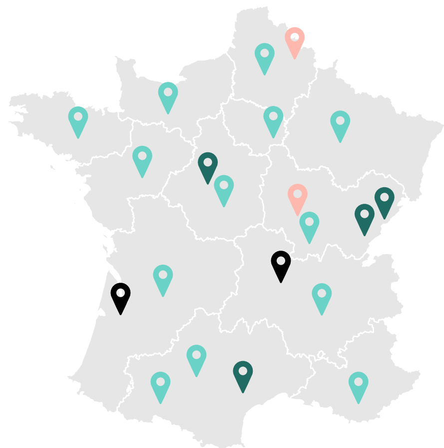
90% of the hydrogen used in industry comes from fossil sources.

Bringing flexibility to the electrical system

Storing electricity chemically for peak shaving

Speeding up the deployment of solar and wind renewable energies

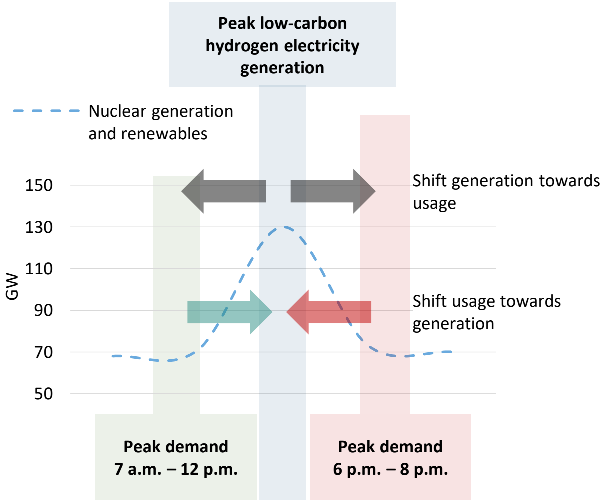
An emerging industrial ecosystem



Electrolyzer gigafactory | Refueling station | Storage infrastructure | Fuel cell production infrastructure

The development of renewable technologies enhances flexibility in the electricity system

An alignment between peak production and consumption, facilitated by the integration of renewable technologies…



…which helps enhance the agility and controllability of the electrical system and reduce electricity network investment and operating costs

1 Supply-side flexibilities through the shifting of renewable production towards peaks in demand thanks to storage and production curtailment

2 Energy storage through the use of stationary batteries and hydrogen (which can later be used in fuel cells to generate electricity)

3 Participation of renewable technologies in balancing mechanisms (adjustment mechanism, as well as primary and secondary reserves)

Producers can leverage a variety of system and adjustment mechanisms managed by RTE allowing them to capitalize financially on their flexibility.

This genuine need represents an opportunity, allowing producers to support the electricity system while earning additional remuneration.

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Overview of the renewables power system

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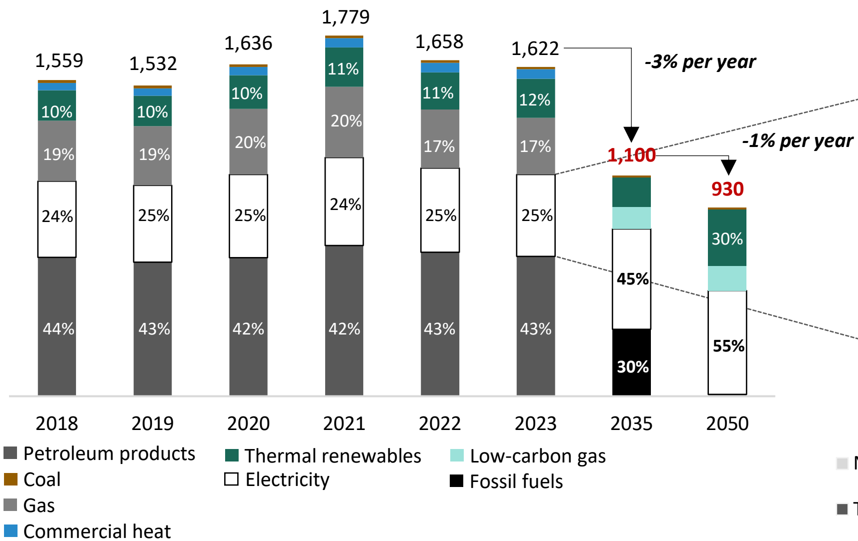
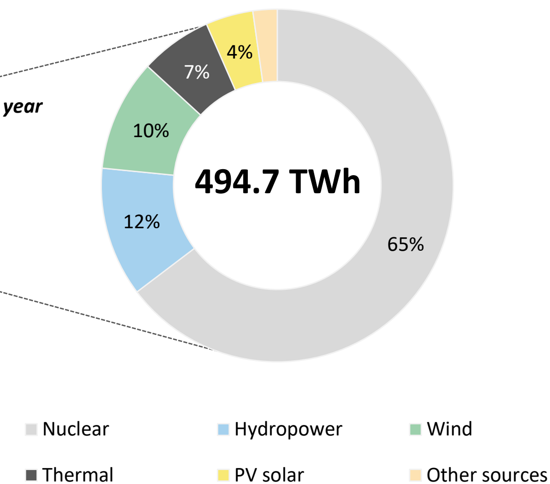
Renewable energies in the energy mix

France's energy pathway must allow fossil fuels to be replaced with renewable electrical sources

Breakdown of final energy consumption in France in TWh



Breakdown of electricity generation in France in 2023



Drivers of decarbonization

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Sources: RTE, Ministry of Ecological Transition, 2035 & 2050: RTE projection scenario A "Successful Acceleration"

The massive electrification of end uses will result to increased electricity consumption despite energy conservation initiatives

Electricity consumption in France

2023: 445.7 TWh → Electrification of end uses **+50%** → **2035: 615[1] TWh** → Energy conservation and efficiency → **2035: 580[2] TWh**

[1] RTE's baseline scenario for 2035 (scenario A) | [2] RTE's "low" scenario A for 2035

INDUSTRY

2023: 103 TWh → +33% → 2035: 160 TWh

The **share of electricity in the final energy mix** of industrial sectors is projected to rise **from 40% to 70% by 2050**.

This development is anticipated as a result of**electrification of industrial processes and heat requirements** the, in particular in industries critical to the energy transition.

TRANSPORTATION

2023: 10 TWh → ×8.6 → 2035: 86 TWh

The electric vehicle fleet is expected to increase sharply, reaching **15 million vehicles by 2035**.

This growth is fueled by **regulations** aimed at decarbonizing transport, including the ban on the sale of internal combustion vehicles, emission standards, and the establishment of low-emission zones, among others.

RESIDENTIAL

2023: 151 TWh → -1% → 2035: 150 TWh

The proportion of homes heated by electricity is expected to rise from 40% to 65% by 2035, driven by the widespread deployment of heat pumps.

Building energy efficiency retrofits and the impact of climate change on winter temperatures are expected to **stabilize residential electricity consumption**, however.

COMMERCIAL

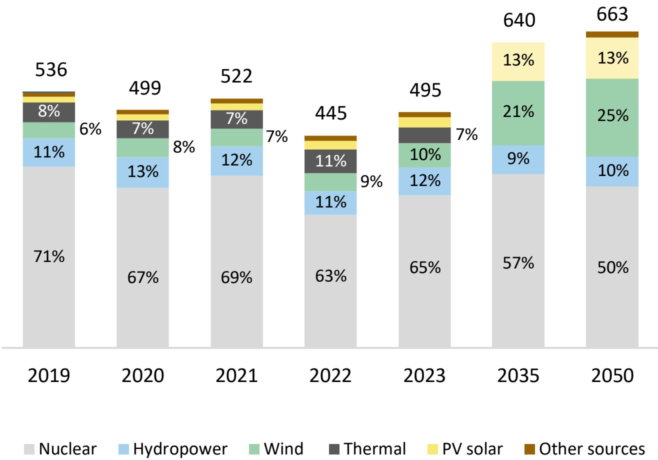
2023: 130 TWh → +7% → 2035: 139 TWh

The improved energy efficiency of buildings, changing working patterns, rising awareness, and behavioral shifts should help contain electricity consumption, despite the massive electrification of end uses such as heating and air conditioning.

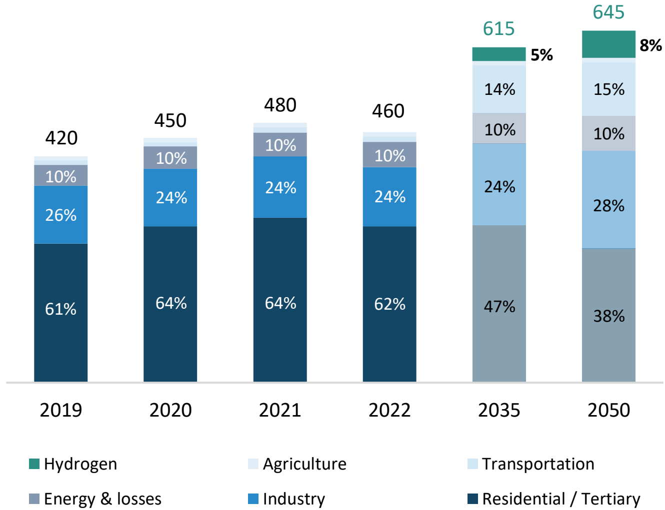
Source: RTE baseline scenario in its 2023 forecast report for 2050, "Bilan prévisionnel 2023 - Futurs énergétiques 2050"

In 2023, renewable electricity production was four times higher than electricity generated from fossil fuels

Net electricity production in France (TWh)



Final electricity consumption by sector in France (TWh)



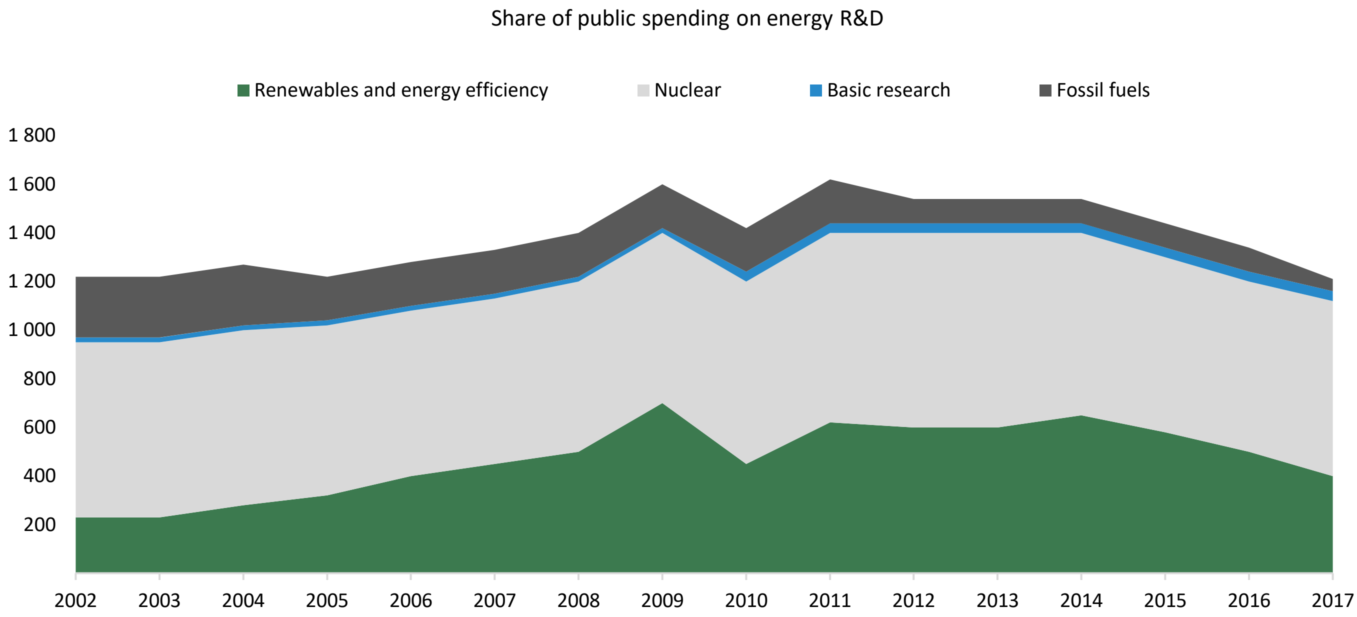
Total electricity production in 2023 amounted to 494 TWh, i.e., 11% more than in 2022. Roadmap to 2050: 30% increase in production

Production from renewable energy amounted to 131 TWh in 2023 – 24% more than in 2022. Roadmap to 2050: significant increase in renewable energy to reach 50% of production.

The electrification of end uses will drive electricity consumption growth in certain sectors, with an increase of +40% for industry. In addition, by 2050, 90% of vehicles will be electric.

Sources: RTE; French Ministry of Ecological Transition, 2035 & 2050: RTE projection scenario A "Successful Acceleration"

Public R&D expenditures have shifted from fossil fuels to renewables



€1.7 billion

invested in 2021 (+12%)

30%

of energy R&D expenditures allocated to renewable energies and energy efficiency

Ø

Phase out public funding for fossil fuel R&D

Sources: RTE; French Ministry of Ecological Transition; France Renouvelables analysis

Boosting financing for renewable energy to accelerate the transformation of energy supply

RECLAIM Finance

Published in 2021, the IEA's "Net Zero Emissions by 2050" scenario outlines a financing pathway to limit global warming to 1.5 °C

The IEA recommends a gradual and rapid reduction in funding for fossil fuels and the immediate end of all support for their expansion. It calls for a massive increase in funding alternative energy sources to fossil fuels through three key approaches: transforming the energy supply system, increasing energy efficiency, and decarbonizing energy end uses.

2030 objectives

+67%
Annual funding for the energy sector must increase from US$2.8 trillion to US$4.7 trillion.

×2.3
Annual funding for alternatives to fossil fuels must increase from $1.8 trillion to date to $4.2 trillion in 2030.

6:1
For every dollar allocated annually to fossil fuels, six dollars must be allocated to alternative, primarily renewable, energies.

In 2023, the clean energy credit financing ratio of French banks averaged 1.66:1. This means that for every €1 directed towards fossil-fuel activities, €1.66 of loans were granted to renewable energy projects and companies.

	BNP PARIBAS	CRÉDIT AGRICOLE	SOCIETE GENERALE	GROUPE BPCE	Crédit Mutuel	LA BANQUE POSTALE
Ratio of renewables to fossil fuels	1.09:1	2.17:1	1.28:1	3.04:1	5.07:1	4.33:1
Renewables exposure (in billions of €)	13.7	20.3	14	10.5	2.4	1.4

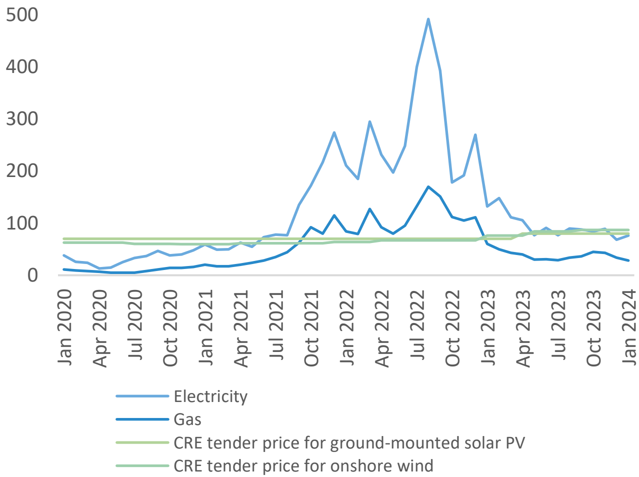
These credit ratios do not fully capture the entirety of the financing provided to the energy sector by French banks, however. Reclaim Finance is currently conducting financial research to calculate a comprehensive clean energy financing ratio that would also account for indirect financing associated with capital market activities.

Funding for the transformation of the energy supply system must be focused on sustainable, commercially mature, and rapid-to-deploy sources and technologies—first and foremost, solar and wind power, storage, and the modernization of electricity networks.

Source: Reclaim Finance

The unstable geopolitical and environmental landscape accelerates the need for renewable energy development

Wholesale electricity and gas prices over time (in € per MWh)



Geopolitical crises significantly impact market prices for fossil fuels, and natural gas in particular

The use of fossil gas power plants in the electricity mix has a significant impact on electricity prices due to the price-setting mechanism (marginal pricing).

In contrast, the prices for renewable electricity production are lower, stable, and uncorrelated with fossil fuel prices, which contributes to reduce electricity costs while securing the supply of electricity.

Nuclear energy may face limitations due to climate change, especially during extreme heat events or droughts, highlighting the essential role of renewable energies.

The post-Covid economic recovery and the onset of the war in Ukraine have had a strong upward impact on the price of these two energy sources.

Renewable energies at the service of energy resilience

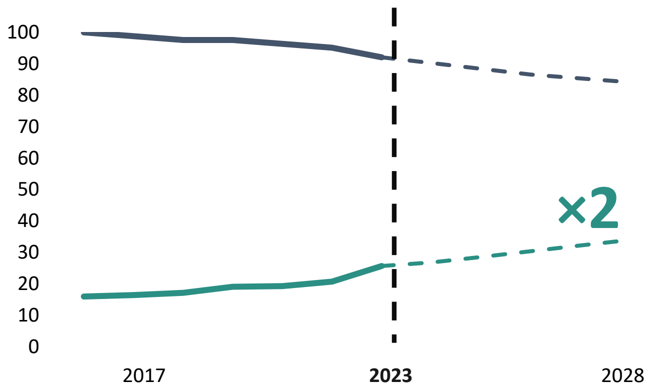
Ensuring energy autonomy and decreasing reliance on imported fossil fuels	Ensuring the security of electricity supply at a competitive price	Enhancing the resilience of the energy system and its capacity to withstand geopolitical crises	Enhancing the flexibility and controllability of the electrical system

Sources: ENTSO-e; RTE; Insee; CRE; IRSN

The PPE outlines France's national objectives for the development of various renewable electrical energies

France's multi-annual energy programming (PPE) is the strategic steering tool defining the country's energy policy. It outlines priority actions to achieve the goals of ecological transition and carbon neutrality. It establishes targets for increasing the share of renewable energy while decreasing final energy consumption and primary fossil fuel consumption.

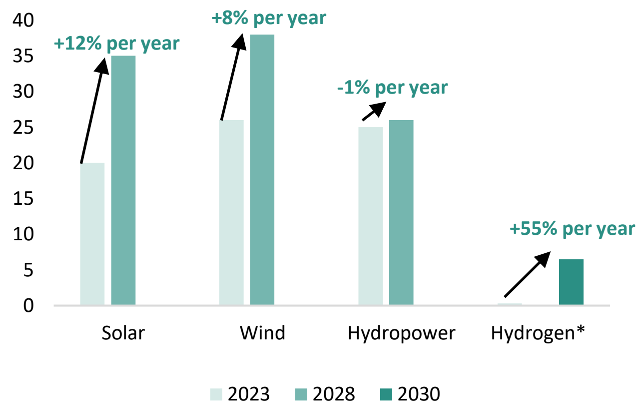
France's current energy situation and the vision set out in the PPE



Final energy consumption, base year 2017

Share of renewable energy in total energy consumption, in %

Capacity targets set by the PPE in GW

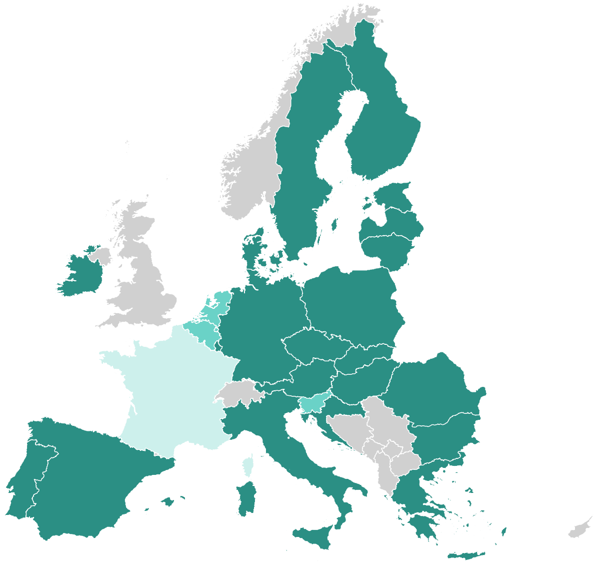


*GW of installed electrolyzer capacity

Sources: Carbon 4; PPE 2020; France Relance 2030; France Renewables analysis

The recently introduced legislation aims to create an enabling environment for realizing the goals of the 2028 PPE

France has achieved 80% of its renewable energy development targets for 2023



Objective exceeded | Objective achieved | Failed to achieve the objective

Timeline of regulatory framework and support mechanisms involved in the 2028 plan

2024: PPE revision
Accelerate grid connections

2023: Law on the acceleration of renewable energy production
Planning the deployment of renewable energies with local elected officials | Simplifying authorization procedures | Mobilizing already artificialized spaces | Benefit-sharing arrangements

2023: Redesigned national tendering process for low-carbon hydrogen
Production support

2023: Changes in CRE's tendering rules for wind power
Production support

2022: Offshore wind pact
Minimum volume of 2 GW per year in awarded tenders and 20 GW by 2030.

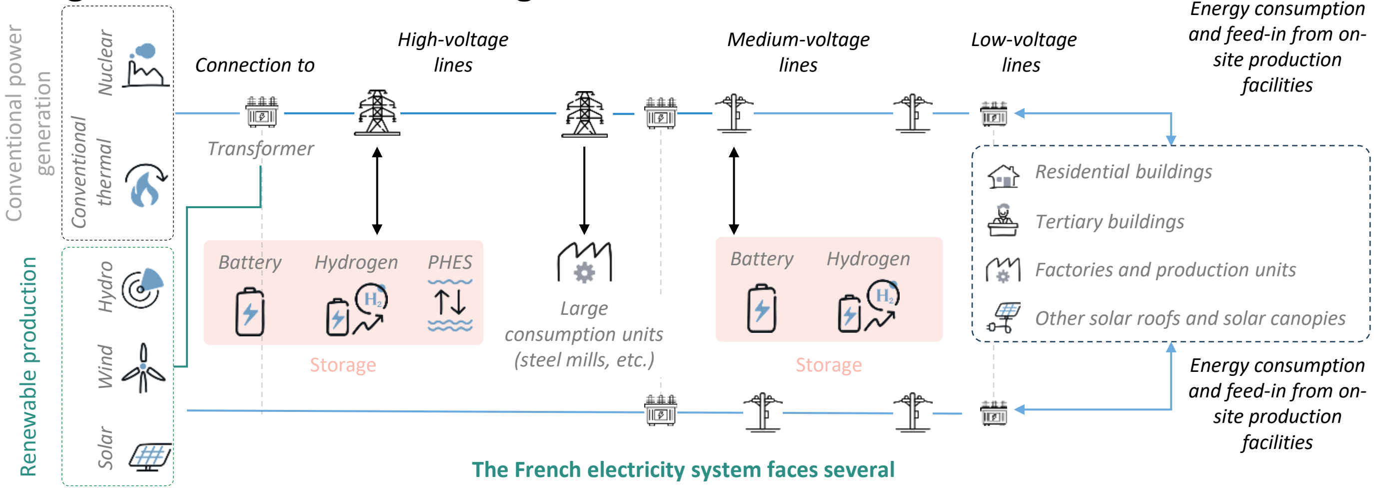
2022: RepowerEU
Doubling the current share of renewable energy in the EU by 2030

Sources: Le Monde; France Renouvelables analysis

1.2

Grid flexibility and balancing

The electricity system is facing new challenges, in part due to the large-scale integration of renewable energies



The French electricity system faces several major challenges in implementing the energy transition

Managing the balance between supply and demand

In a context of increasing variability in consumption and production—due to the electrification of end uses and the integration of renewable energies—**the real-time balancing of power feed-in and power consumption** becomes more complex to manage."

Adapting to climate change

System operators must **adapt their infrastructure to the increasing frequency and intensity of climatic events** and size electrical systems according to the impacts of climate change.

Accelerating the integration of renewable energies

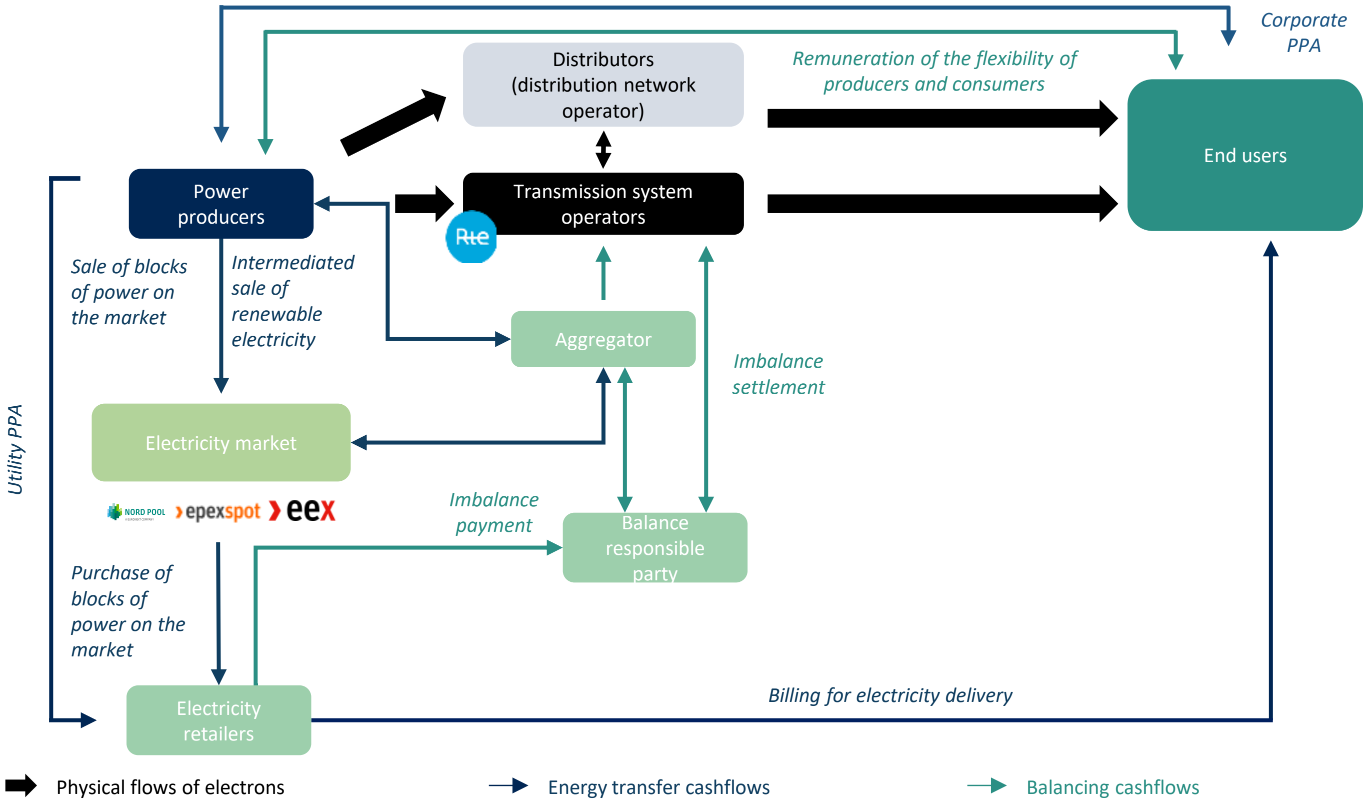
The massive deployment of renewable energies is transforming the **electrical system into a decentralized network of power generation assets with the emergence of producers-consumers**. The way the electrical system is managed must evolve to integrate these new components

Ensuring electricity is competitive

Access to affordable electricity is essential for maintaining the competitiveness of the French economy and ensuring households have access to this basic necessity amid the electrification of end uses.

Sources: Wind Observatory 2023; Capgemini Invent analysis

The French electricity system involves multiple actors interacting through physical and financial flows



Source: Capgemini Invent analysis

Different types of flexibility options are used to ensure the electrical system is optimally balanced

Flexibility is the electrical system's ability to leverage the variability of a power generating asset or consumption unit.

Demand-side flexibilities

Demand response, adjusting demand to available resources and for voltage control on the electricity system (reducing consumption during **peak periods**, shifting electricity demand to times when power is **abundant and inexpensive**).

Supply-side flexibilities

Up-regulation or down-regulation of generation (in the event of excess load or excess production, respectively). Thermal and hydraulic power stations can modulate production both upwards and downwards. **Renewable technologies** can mainly adjust their production **downwards**.

Energy storage

Energy storage systems can take various forms (PHES, batteries, etc.). They allow **electricity to be stored during periods of excess production and allow for the release of stored electricity back to the grid during times of high demand**.

The benefits of flexibility

Load shifting

Ensure network balancing while limiting the need to activate costly balancing mechanisms for users.

Smoothing prices

Reduce consumption peaks that trigger the use of fossil fuel power stations with high marginal production costs.

Lower costs

Reduce investment needs required to strengthen the network's transmission and distribution capacities.

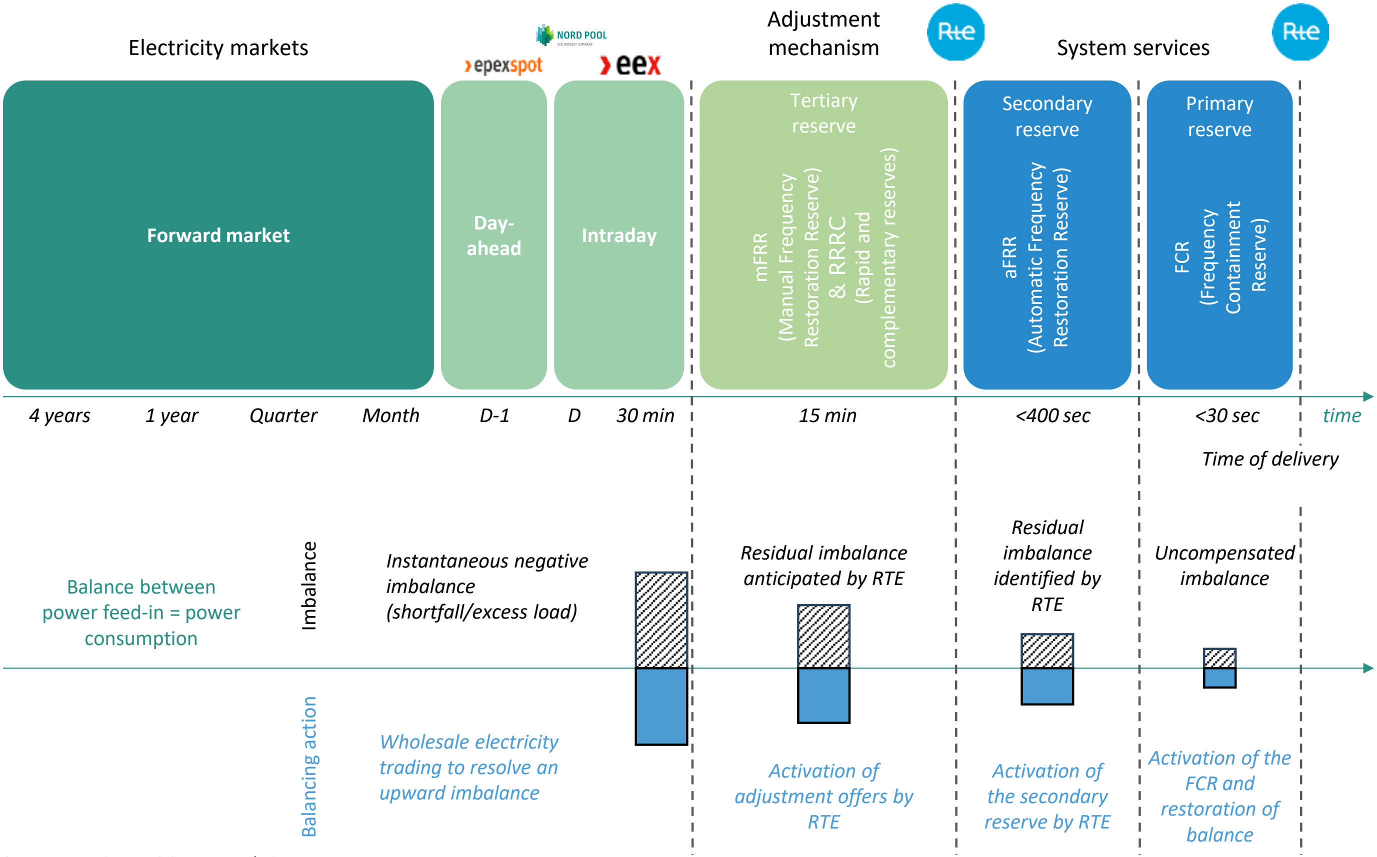
RE integration

Maximize the integration of renewable energies and the feed-in of renewable energies into the electricity system by improving how their variability is managed

● Structural benefits ● Economic benefits ● Environmental benefits

Sources: ADEME "Flexibilité du système électrique" [Flexibility of the electric system]; RTE

These flexibilities are activated through several balancing mechanisms.



Sources: RTE; Capgemini Invent analysis

Summary on grid balancing mechanisms

	Markets	Adjustments	System services

Capacity (€ per MW)

Capacity mechanism

This mechanism requires electricity retailers to purchase capacity guarantees to ensure electricity supply during winter peak periods. These guarantees are purchased from operators with generation or load reduction capacities who undertake to make their capacities available.

Power (€ per MW)

Wholesale market

Electricity retailers purchase large volumes of electricity from power producers and aggregators to ensure coverage of the needs of their customers (resource adequacy) on the spot markets (with same-day or next-day delivery) and on forward markets (several months, quarters, or years before actual delivery).

Adjustment mechanism

A balancing responsible party, liaising with power producers and consumers, submits balancing energy bids. Those that meet the balancing need of the network are activated by RTE in order of economic precedence (common merit order)

Load reduction mechanism

Individuals and businesses are asked to temporarily reduce their consumption during peak periods. These load reductions can be traded on the wholesale market (through the NEBEF mechanism) or through the adjustment mechanism (via the tertiary reserve).

System services

Primary reserve (FCR)

Decentralized, automatic activation within a synchronous area to contain system frequency after frequency deviations The entire primary reserve of each power-generating asset can be mobilized in under 30 seconds.

Secondary reserve (aFRR)

Automatic activation (<400 s) following a centralized order from RTE, in the event that the activated FCR is insufficient to restore network stability. All producers generating more than 120 MW of power are required to take part in aFRR.

Rapid and complementary reserve (RR)

Reserves available to restore or support the secondary reserve in under 30 minutes. The rapid reserve (1000 MW) can be activated in under 15 minutes and the complementary reserve (500 MW) in under 30 minutes.

Source: RTE

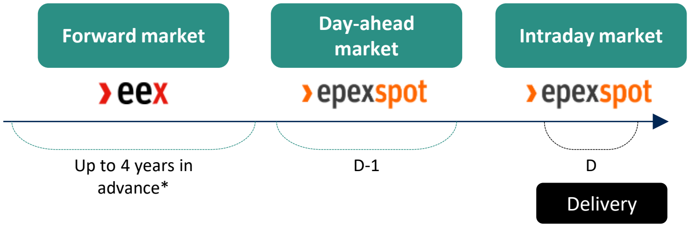
Electricity markets

Elements of a definition and features

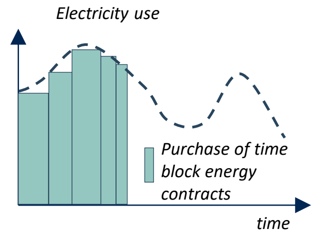
Electricity markets enable participants (power producers, aggregators, and electricity retailers) to trade volumes of energy to meet consumer needs. These transactions take place on two marketplaces:

- On the forward market managed by EEX, volumes of energy are traded with physical delivery periods in the following month, quarter or year (up to 4 years from delivery).
- On the spot market managed by EPEX SPOT, volumes of energy can be traded for delivery the next day (day-ahead market) or the same day (intraday) up to 30 minutes prior to delivery.

How the electricity market works



Electricity retailers purchase energy volumes based on forecasts of their customers' consumption to ensure the balance between power feed-in and withdrawals.



Two different types of electricity products are traded:

***Base**: continuous delivery of power at a constant rate throughout the year;*

***Peak**: delivery of power at a constant rate from 8:00 AM to 8:00 PM from Monday to Friday*

Trading activity on the electricity markets

718 TWh

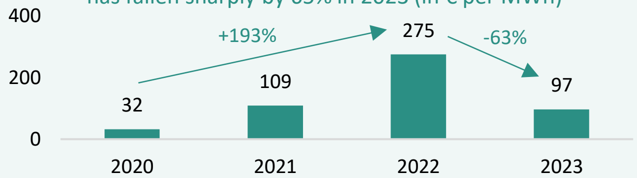
Trading activity on the EPEX spot market in 2023: 75% (542 TWh) on the day-ahead market – 15% (176 TWh) on the intraday market

8,660 TWh

Trading activity on the forward market (EEX) in 2023

Power generation assets involved

The average spot price on the wholesale market has fallen sharply by 65% in 2023 (in € per MWh)



Sources: EEX; EPEX Spot; SirEnergies

System services for frequency maintenance

Elements of a definition and features

There are two kinds of system services for frequency maintenance

- **Primary reserve**: Automatic generation control provided by power plants connected with a reaction time of under 30 seconds for the purpose of frequency containment In France, primary reserves are procured daily using a tendering process conducted the previous day (D-1) by RTE.
- **Secondary reserve**: Power adaptation activated by RTE with a reaction time of under 400 seconds. France's secondary reserve amounts to 500–1,180 MW. In France, all producers operating production facilities with a capacity exceeding 120 MW are required to participate.

Reserve capacities

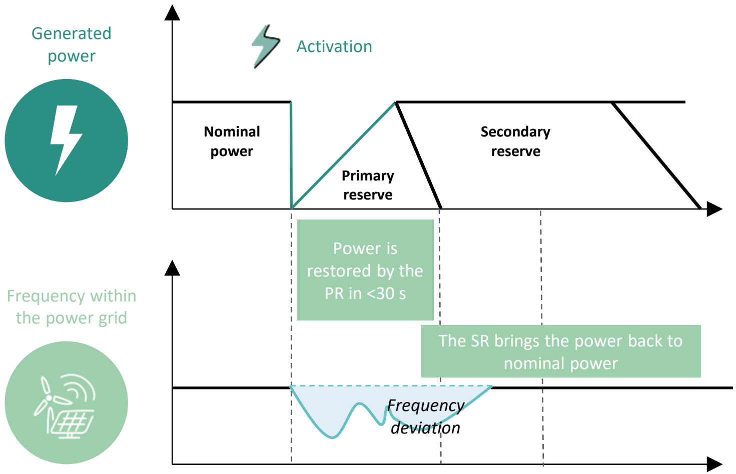
500 MW	500–1,000 MW
Primary reserve	Secondary reserve

Power generation assets involved

Hydropower | Thermal | Nuclear | Storage

Sources: RTE; CRE

How system services for frequency maintenance work



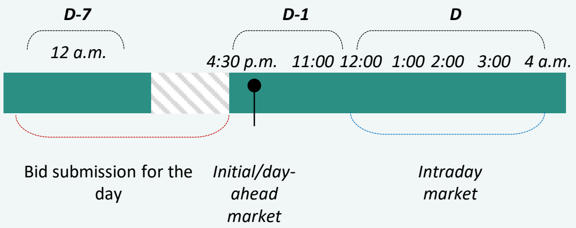
The current pricing system is undergoing complete transformation

A transition to market-based pricing via a bidding process for secondary reserve frequency restoration (aFRR) has been effective since June 19, 2024 Since this date, RTE has been procuring secondary reserve capacities on a daily basis through tendering.

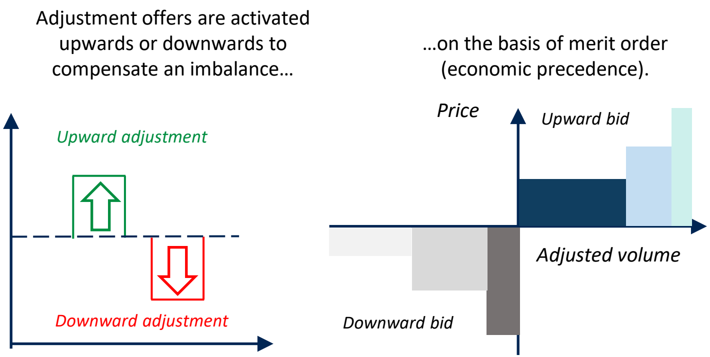
Adjustment mechanism

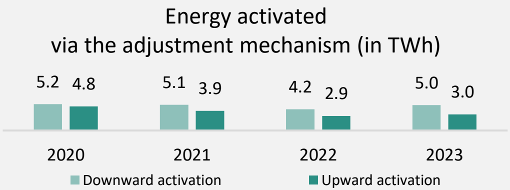
Elements of a definition and features

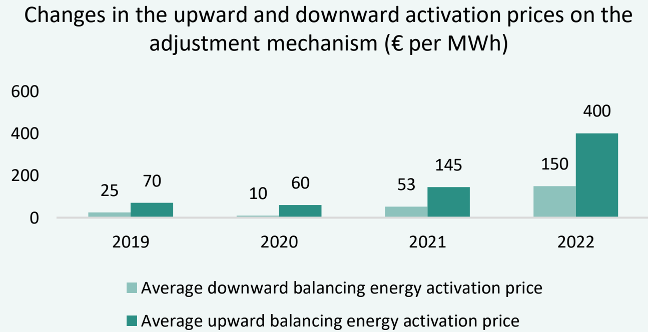
The adjustment mechanism lastingly restores the balance between electricity supply and demand; RTE selects bids based on their suitability for the scale and duration of the imbalance, in order of technical and economic precedence (merit order).



How the adjustment mechanism works







Power generation assets involved

Thermal | Nuclear | Hydropower

Source: RTE

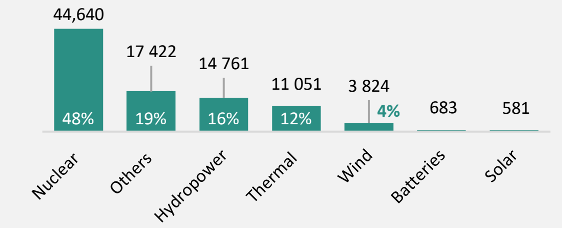
Capacity mechanism

Elements of a definition and features

The capacity mechanism aims to ensure coverage of electricity supply during the winter peak periods. All electricity retailers must secure enough capacity certificates to cover the electricity consumption of their customers.

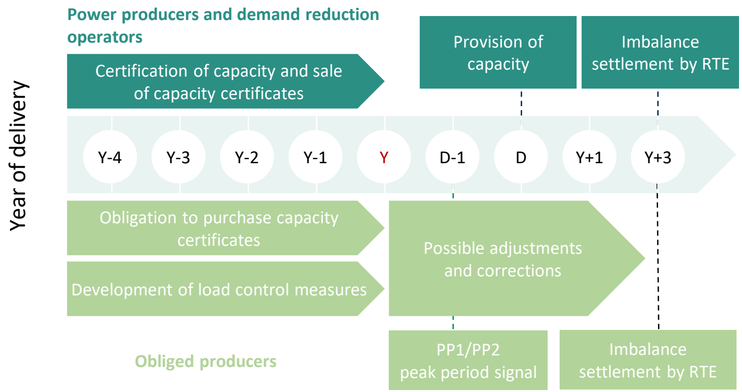
These capacity certificates can be obtained from power producers and demand response operators, who get their load reduction capacities certified by RTE each year: Capacity operators undertake to make their capacities available while obliged producers must be able to cover their customers' consumption over the period.

Breakdown of volumes of capacities certified by RTE (in MW)



93 GW
volume of capacities certified by RTE in 2024

How the capacity mechanism works (certification and capacity certificates trading)



Capacity certificates price

€0.39
Capacity guarantee traded in 2023

€0.11
Capacity guarantee traded in 2024

Power generation assets involved

Sources: RTE; CRE

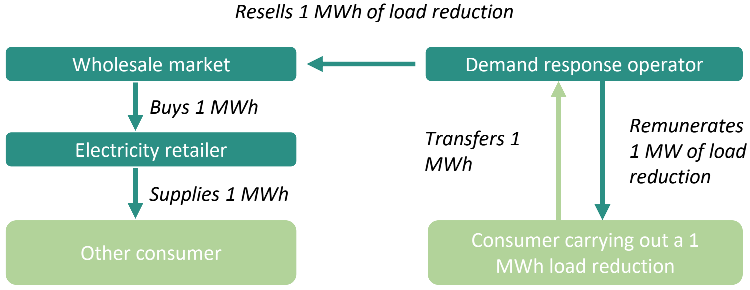
Load curtailment mechanism

Elements of a definition and features

Individuals and businesses can capitalize on their ability to temporarily reduce their electricity consumption during peak consumption periods. These load reduction capabilities can be traded by demand response operators through three mechanisms:

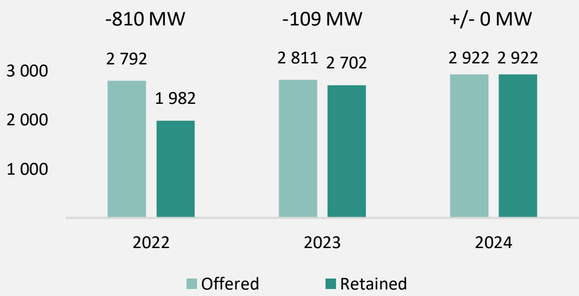
- Implicit demand response, with load reductions obtained in the context of a market offer between an end consumer and its electricity supplier/retailer
- NEBEF: unused energy is exchanged in the form of blocks on the wholesale power markets
- The adjustment mechanism piloted by RTE

How the load reduction mechanism works (case of remuneration through the NEBEF mechanism)

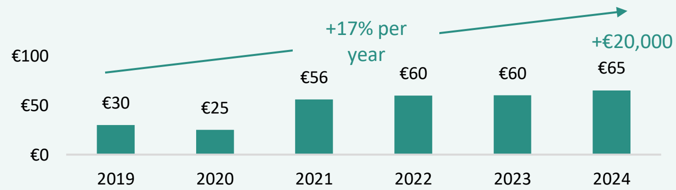


The electricity retailers involved take on the role of demand response operators. Consumers, lacking access to market information, must necessarily rely on a demand response operator.

Offered and retained load reduction capacities (in MW)



Remuneration of selected tenderers for load reduction (in k€ per MW)



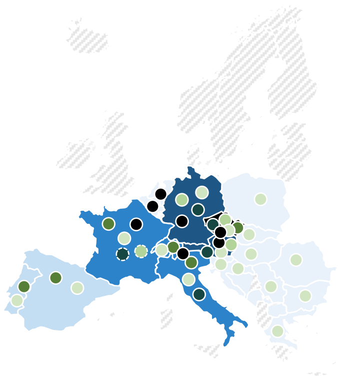
In 2023, the remuneration for the winning facilities in the flexibility tenders was established at €59,900 per MW. In 2024, the ceiling was increased to €65,000 per MW (+8.5%).

*A bonus of €20,000 is currently being introduced for facilities carrying out recurring load reductions.

Sources: RTE “Appel d’offre d’effacement 2023” [2023 load reduction tenders]; Connaissances des Énergies

These balancing mechanisms are being consolidated at the European level

European countries take part in the electricity system's various balancing mechanisms



- FCR – primary reserve
- TERRE – for RR (replacement reserves) process
- IGCC – for imbalance netting process (coordination and exchange between TSOs)
- PICASSO – for aFRR/secondary reserves process
- MARI – for mFRR/adjustment
- Balancing mechanism being implemented

Number of platforms on which the country is present:

5 | 4 | 3 | 2 | 1

Sources: RTE; Toute L'Europe "Marché de l'électricité" [Electricity market]

There are currently over 400 cross-border electricity interconnections across Europe

Europe's interconnected electricity system allows it to boost the security, efficiency and sustainability of its electricity supply

Strengthening grid stability

Sharing electricity at the European level allows for better management of fluctuations in demand and production, while providing a more effective response to imbalances.

Price reduction

Interconnecting networks lowers prices by promoting competition between national markets, allowing the transfer of electrons from low-cost regions to higher-cost ones.

Mobilization of renewable energy sources

Cross-border electricity connections allow surplus electricity to be transferred during favorable weather conditions to areas where consumption is higher.

Security of supply

In the event of a shortage in any given country, electricity can be imported from neighboring countries, thus ensuring a more stable and reliable supply.

2 Current state of development and prospects of the renewables sectors

2.1

Onshore and offshore wind

In 2023, wind power reached a significant milestone by supplying over 10% of France's electricity consumption and exceeding 30,000 jobs

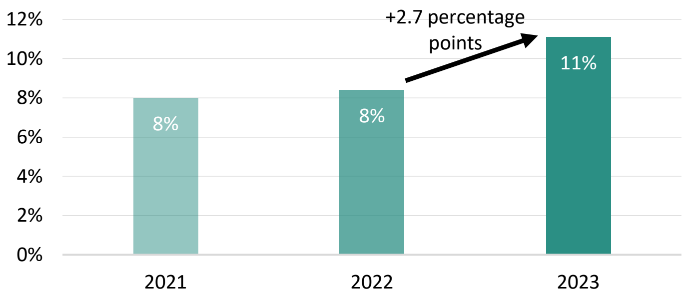
1.3 GW
in wind power capacity commissioned over the course of the year

50.6 TWh
of electricity is generated from wind power

31,447 jobs
(both direct and indirect)

Electricity generation equivalent to the power use of **23 million people**

Growth in electricity consumption coverage



- **>9,500 wind turbines** in France, spread across almost **2,391 wind farms** (including 7 offshore wind farms) at the end of 2023
- Wind power is France's **2nd largest source of renewable power** after hydropower, and the 3rd largest source of electricity generation overall.
- France is **Europe's 4th largest product of wind-generated electricity**, accounting for over 10% of the continent's total production.
- Around 124 MW of wind power capacity has been repowered in France in recent years.

Sources: French Ministry of Ecological Transition, Agence ORE, RTE, Engie

Key figures for onshore wind power

49 TWh Electricity production in 2023	**22 GW** Installed capacity as at 31 Dec 2023, including 1,300 MW installed in 2023
23,607 direct and indirect jobs in the industry in 2023	**€6.2 billion** Industry turnover in 2022
>700 companies involved	**24,1 GW** **34,7 GW** PPE objectives for 2023 and 2028

Value generated (excluding energy sold):
€1,500 million

Key figures for offshore wind power

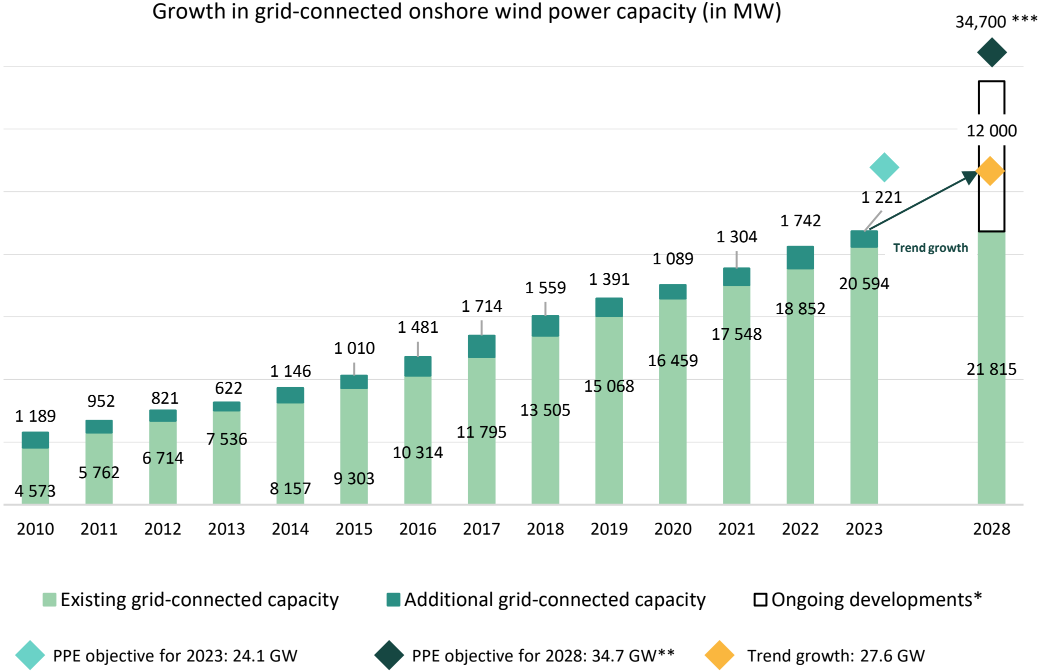
1.9 TWh Electricity production in 2023	**800 MW** Grid-installed capacity as at 31 December 2023
7,840 direct and indirect jobs in the industry in 2023	**≈ €3.5 billion*** Industry turnover in 2023
235 companies involved in 2022	**5,2 GW** **–6,2 GW** PPE objective for 2028

€3.8 billion invested in 2023

Sources: Agence ORE; Enedis; RTE*; ADEME “Marchés et emplois dans le secteur des énergies renouvelables et de récupération” [Markets and jobs in the renewable energy and energy recovery industries] – Provisional estimate ** Observatoire de l’Énergie de la mer 2023 [Observatory of marine energies] *** Excluding energy sold

France is improving its momentum but it remains insufficient to achieve the objectives of the 2028 PPE

Growth in grid-connected onshore wind power capacity (in MW)



Achieving the objectives of the 2028 PPE will require doubling the rate installation of new, grid-connected wind power capacity with an **additional 12 GW and to expedite the allocation of projects. At the current rate, the country will be deprived of 7 GW of onshore wind power.**

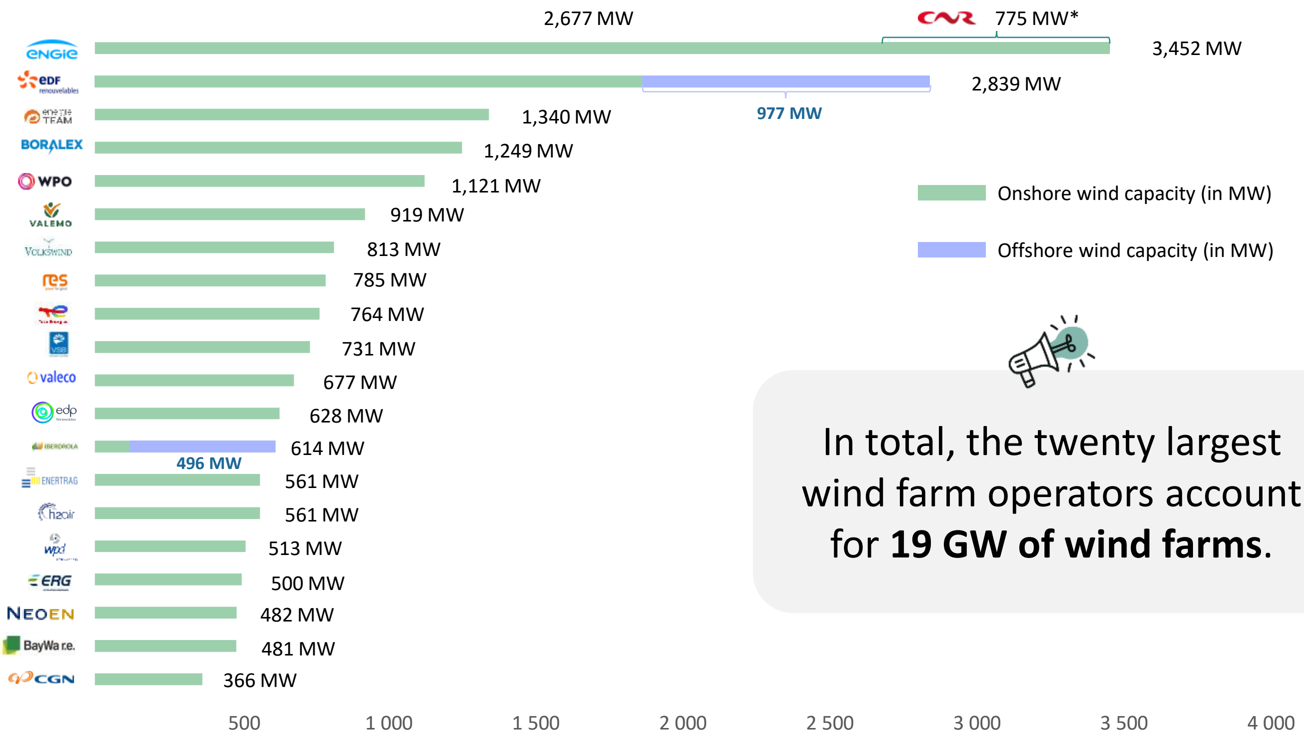
** Projects for which there has been a proposal for queuing or an accepted technical and financial proposal. **This corresponds to the "high" scenario of 2028 PPE *** This figure is only valid for onshore wind power.*

Source: Agence ORE (the consortium of France's electricity and gas distributors)

Overview of installed wind power capacity

Top 20 onshore and offshore wind farm operators in France as at 30 June 2024

MW in operation, either managed directly or on behalf of third parties



In total, the twenty largest wind farm operators account for **19 GW of wind farms**.

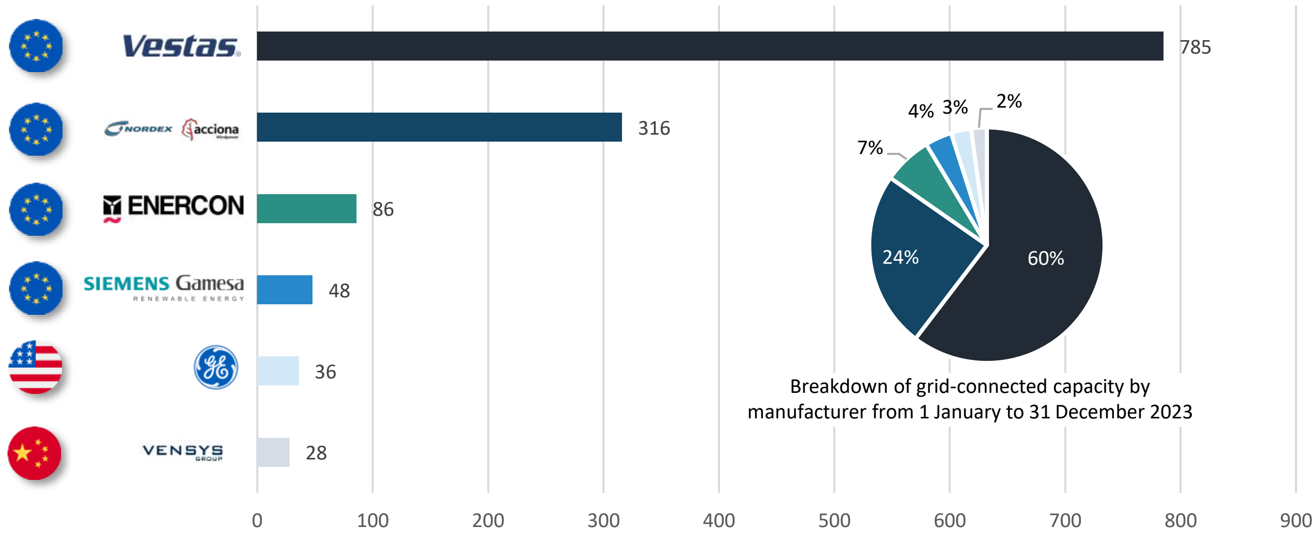
Source: France Renouvelables 2024 study

*The CNR MW are operated at a rate of 474 MW by Energieteam and 108 MW by Engie Green, the remainder by third parties

In 2023, the turbine construction market is primarily dominated by European manufacturers

In France, turbine manufacturers have installed 1,299 MW of wind power capacity in 2023, with European manufacturers accounting for 95% of the installed capacity in onshore wind.

MW connected to the grid by the 6 main manufacturers from 1 January to 31 December 2023

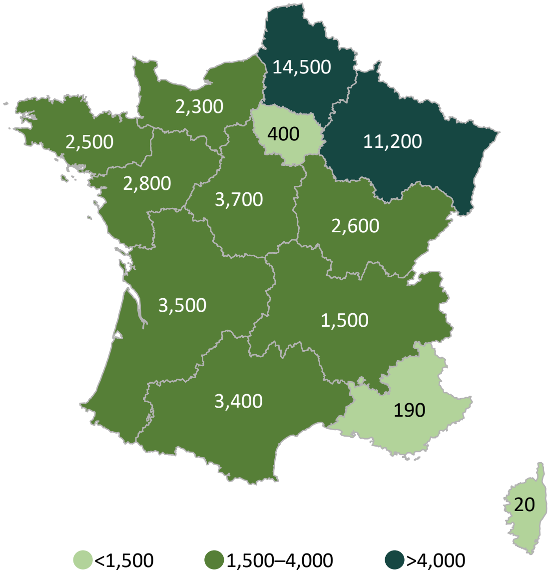


Breakdown of grid-connected capacity by manufacturer from 1 January to 31 December 2023

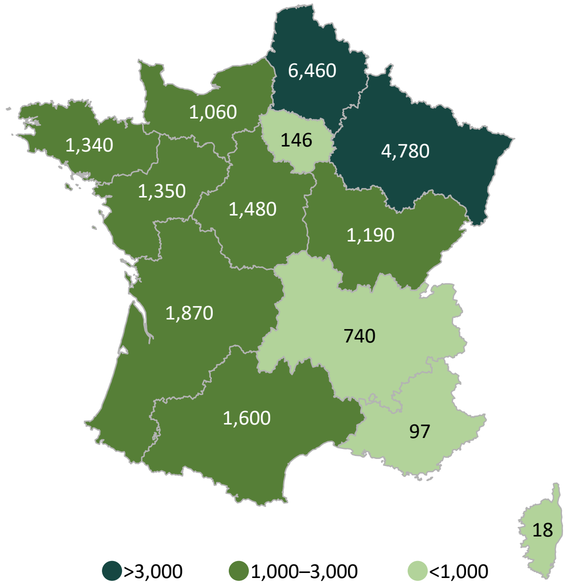
Source: France Renouvelables analysis

Wind-generated electricity production is primarily concentrated in the northern and eastern regions of France

Onshore wind power production (in GWh)
by region in 2023



Grid-connected capacity (in MW)
by region as at 31 December 2023

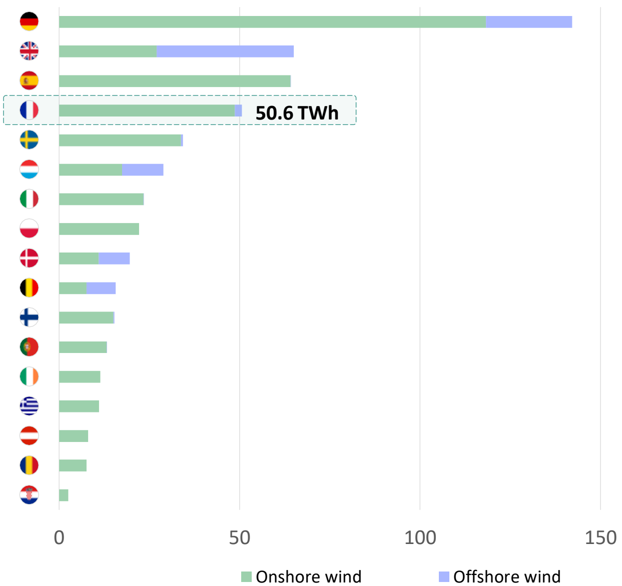


Grid-connected capacity is mainly concentrated in the north-eastern regions of the country. As a result, wind-generated electricity is significant in these regions.

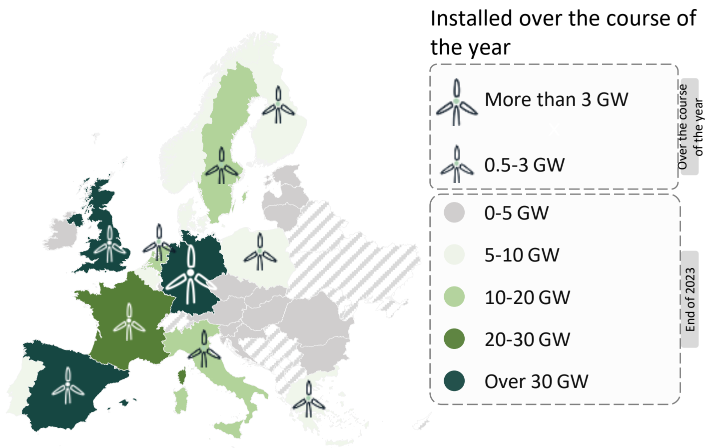
Sources: Agence ORE; Enedis; RTE

As a result of this momentum, France has become a key driver of the development of the wind industry in Europe

Wind power generation in Europe (in TWh)



Installed onshore and offshore wind power capacity by country in Europe at the end of 2023



The European target (excluding the UK) for 2030 is to reach 425 GW, requiring an increase of 200 GW over the next 6 years, i.e., 30 GW per year.

Although wind energy only represents 11% of France's energy consumption, the country remains the 4th **largest producer of wind electricity in Europe**.

In 2023, 16.2 GW of new wind capacity were installed across the EU, bringing the total wind capacity to 218 GW. With 1.3 GW connected to the grid in 2023, France accounted for approximately 10% of the new capacity installed in Europe that year.

Sources: WindEurope; Ember

The multiple benefits of the wind market

The development of wind power in France brings about benefits at all scales and for all stakeholders.

SOCIETY AND ECONOMY

Wind power is a renewable, low-carbon energy source. It is a competitive technology in terms of costs and speed of deployment. The expansion of the industry also creates jobs and drives economic activity and contributes to France's industrial sovereignty

A production cost of €82 per MWh and a deployment time of 7 years for onshore wind power.

BUSINESSES

Corporate Power Purchase Agreements (CPPAs) allow wind developers and companies to enter into direct contracts for the purchase of renewable electricity at prearranged, fixed prices over the long term. The price of electricity can therefore be decorrelated from market prices, and thus help companies obtain low-carbon electricity at a competitive and secure price over the long term in a context of highly volatile energy prices.

Almost 500 GWh of contracts were announced for 2023, i.e. 2.6 times the cumulative number of CPPAs in France at the end of 2022.

FRENCH STATE

Wind power is becoming a major source of revenue for the state. Through the additional remuneration (CR) mechanism, the wind industry as a whole has contributed several billion euros to the French state's general budget in 2022 and 2023.

More than €5.79 billion were returned to the state budget for 2022 and 2023 through the CR ("additional remuneration") mechanism.

LOCAL GOVERNMENT

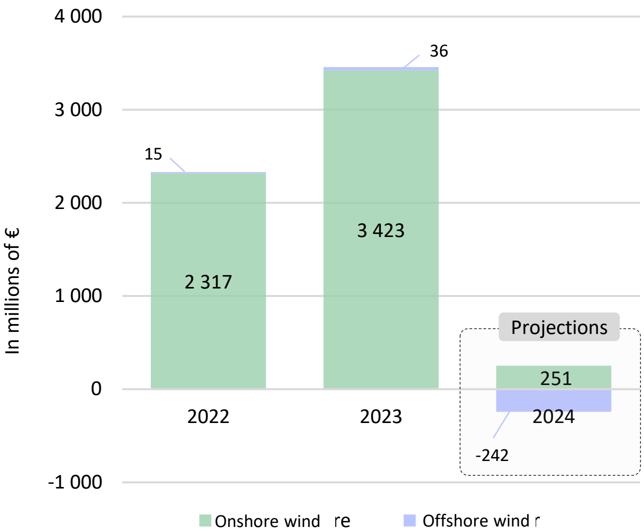
The combination of the flat tax on network infrastructure companies (IFER) for onshore wind power and the tax on offshore wind turbines will enable the industry to contribute several billion euros to local government budgets over the long term. Local authorities will then be able to reinvest these proceeds to reduce local taxes and/or finance public interest projects within their jurisdictions.

The IFER for onshore wind power has contributed around €184 million towards local government budgets, while the IFER for offshore wind power has generated around €10 million in tax revenues.

Over a two-year period, the industry has already repaid 50% of the sums invested by the French government between 2003 and 2021

Thanks to the additional remuneration mechanism, the wind industry has generated several billion euros in revenues for the French state since 2022 and helped tamper volatility in consumer prices.

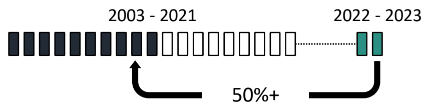
Historical data and projections of the tax contributions raised for the French state through the wind power “additional remuneration” mechanism



+€5.79 BILLION

Net contribution of wind power to the state budget over 2 years, in 2022 and 2023, through the “additional remuneration” mechanism

Over the course of 2 years, the industry has repaid 50%+ of the amount invested by the French state between 2003 and 2021 through the CR mechanism:

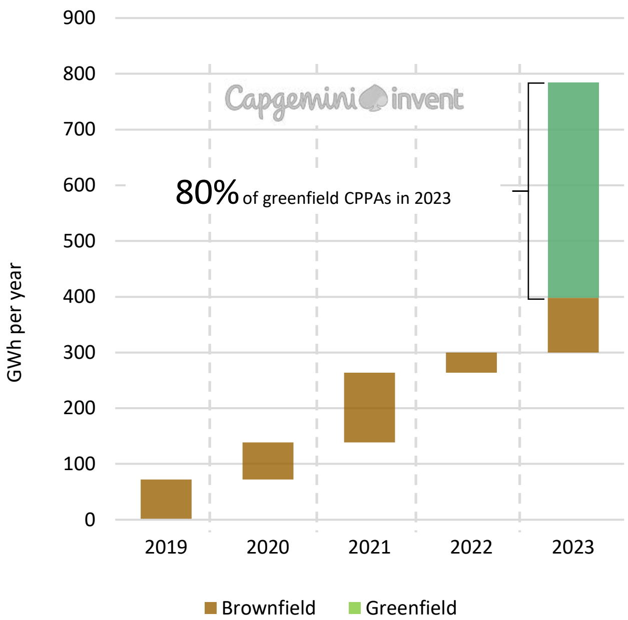


Source: 2024 Evaluation of the CSPE tax to be offset, French Energy Regulatory Commission (CRE) deliberation No. 2024-139

A record year for wind CPPAs, which proved very attractive for electricity-consuming companies

Many Corporate Power Purchase Agreements were signed for “greenfield” wind projects in 2023.

Growth in announced volumes of wind CPPAs in France



Source: Capgemini Invent

+484 GWh per year

in **wind CPPAs** announced in **2023**

+386 GWh per year

in **greenfield wind CPPAs** announced in **2023**

2023 was a record year for wind CPPAs with 9 contracts announced, amounting to a total volume approaching **500 GWh per year** where the combined volumes of the preceding years (2019 to 2022) was only 300 GWh per year.

The year 2023 saw the signing of the first greenfield wind CPPA in France, initiating a strong momentum around this new type of agreement. A total of 5 such contracts were established throughout the year, facilitating the development of 160 MW of new renewable electricity production capacity.

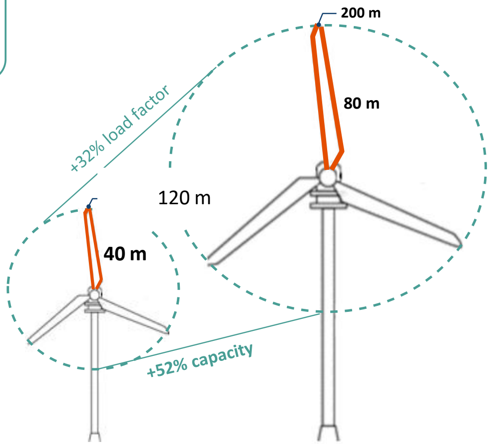
Repowering makes it possible to significantly increase electricity generation for an unchanged number of wind turbines installed.

Repowering a wind turbine

Load factor

Expressed as a percentage, the load factor is the ratio between the power produced by a wind turbine over a given period of time and the nominal power that it would have produced over the same period had it been constantly operating at maximum capacity.

Low capacity: X-80 to 82
Capacity (in MW): 1.5–3
Load factor: 23%
Number of full-load hours: 2015 hours
Nominal rating: 4,533 MWh
Starting speed: 4 m/s
Launch year: 2011
Number of households supplied: 2,266 people



Mast **height: 80 m**

Mast height: 120 m

High capacity: X-160 to 163
Capacity (in MW): 4.2–4.5
Load factor: 31%
Number of full-load hours: 2715 hours
Nominal rating: 11,800 MWh
Starting speed: 3 m/s
Launch year: 2022
Number of households supplied: 5,906 people

Features of large-size turbines

The improved performance of the latest generation of turbines can be attributed to several factors: they operate at greater heights, where wind deposits are stronger and more consistent; they have a larger swept area, which allows for more wind capture; the turbines themselves have higher nominal power ratings and improved start-up capability at lower wind speeds.

1 "repowered" wind turbine

2.5× power generated → +52% in IFER tax revenues for local authorities → More competitive electricity

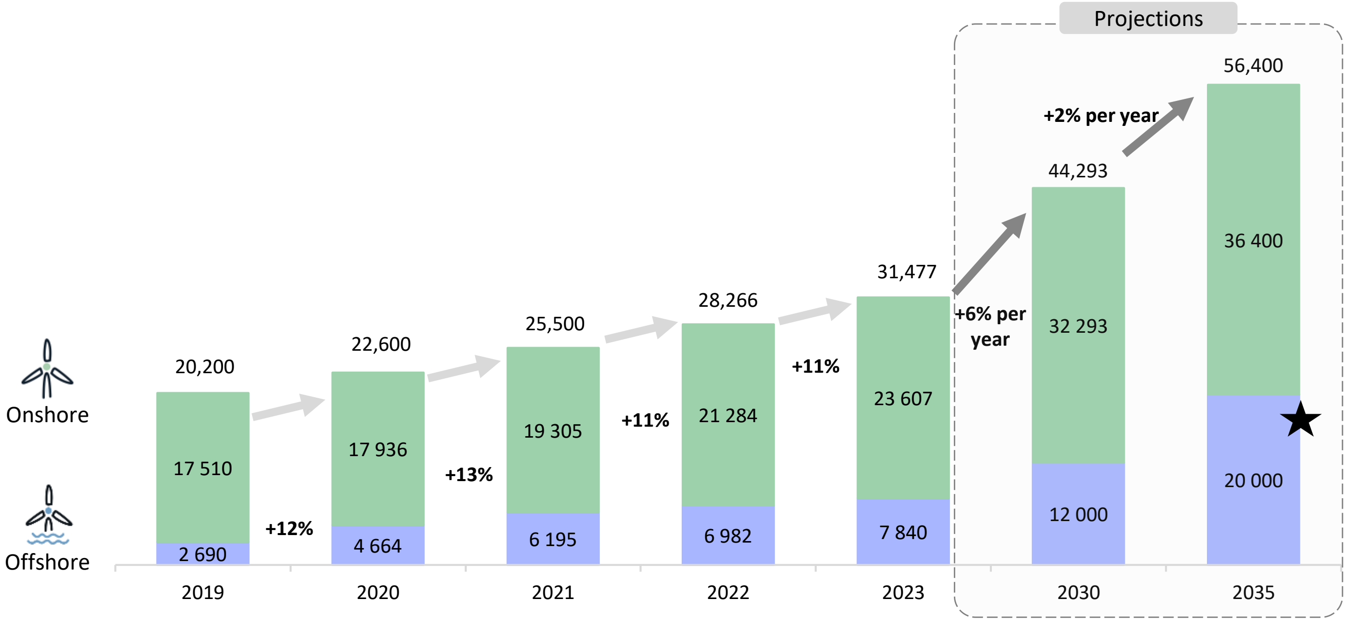
2× more residents powered by wind-generated electricity

Source: WindEurope

**Subject to equivalent costs of raw materials and financing*

Employment in the wind industry has sustained double-digit growth for 5 years and is projected to exceed 40,000 jobs by 2030

Growth trajectory of jobs in onshore and offshore wind
Historical data for 2019 to 2023, and forecasts for 2030 and 2035



Employment growth is supported by the "Planning & development" link in the value chain, which represents one third of jobs in France and has experienced a **15% increase between 2022 and 2023**.

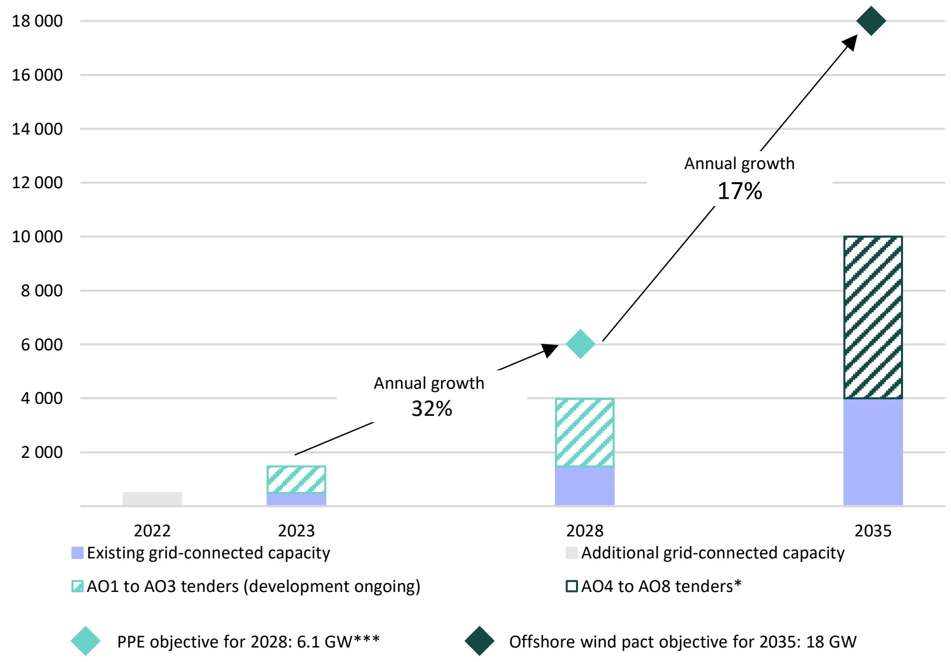
Sources: Analysis by France Renouvelables; Invent

Objective set by the Offshore Wind Pact ★

An insufficient number of ongoing projects jeopardizes the achievement of the 6.1 GW target

2023 national targets achievement rate of 61%

Changes in grid-connected capacity in MW



Insufficient number of projects planned to achieve the objectives of the PPE for 2028 and the Offshore wind pact for 2035.

New ministerial decisions are expected to help **achieve a sufficient volume of projects and meet the objectives of the Offshore wind pact**.

Sources: France Renouvelables analysis, Eoliennesenmer.fr

**Awarded projects with milestones that are not yet known*

A French offshore wind industry that is present across the entire value chain and across the whole country

€3.2 billion*
Total projected value of domestic investment in offshore wind[1] in 2022

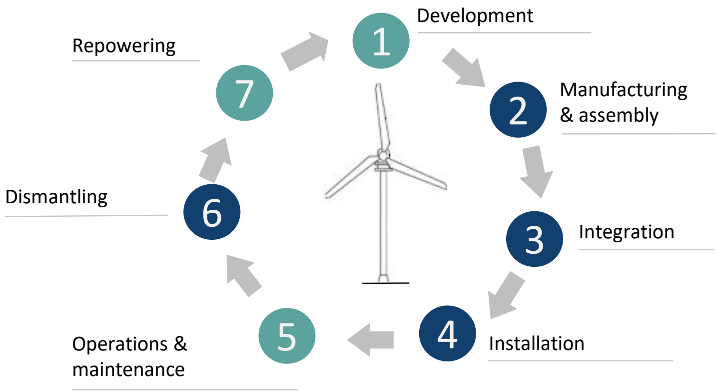
€830 million
Total projected value of exports in 2022

€144 million
Value of MRE-related port investments in 2023

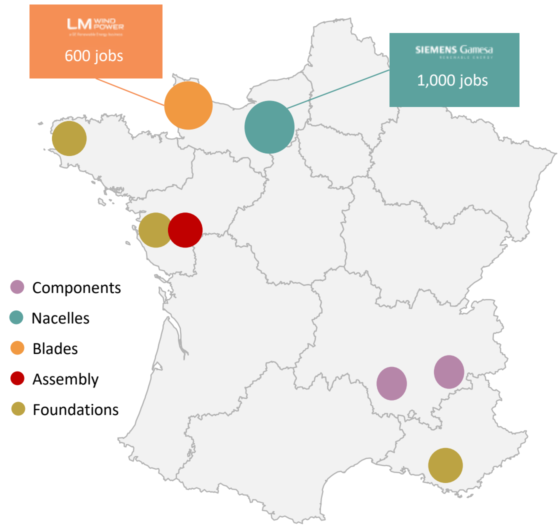
€1.46 billion
Export turnover by offshore wind companies

€3.8 billion
€3.8 billion invested in offshore wind power in 2023

From design to recycling: France's wind industry is present at all links in the value chain



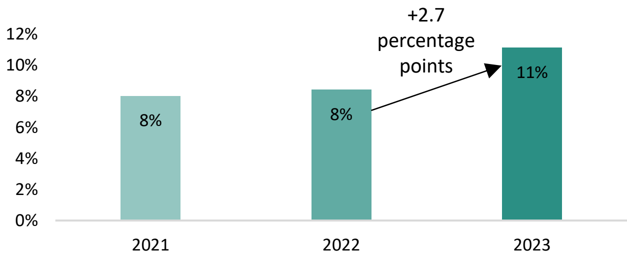
Industrial activities in offshore wind are primarily concentrated in northwestern and southeastern France



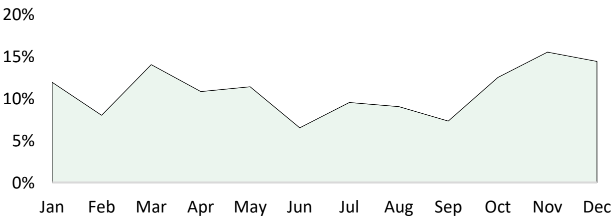
*Source: ADEME "Marchés et emplois dans le secteur des énergies renouvelables et de récupération" [Markets and jobs in the renewable energy and energy recovery industries]
** Source: 2023 Observatory for marine energies
[1] Domestic investment = value of wind assets installed on French territory

In 2023, wind power will cover more than 10% of French electricity consumption, i.e., as much as hydroelectricity

Growth in electricity consumption coverage

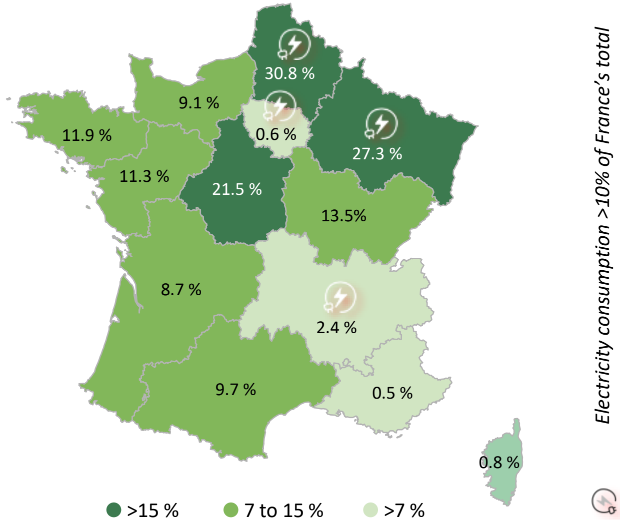


Monthly consumption coverage for the year 2023



The coverage of electricity consumption by wind power has experienced constant growth over the last 3 years. In 2023, wind power covered more than 11% of electricity consumption in France. Wind power generation is particularly efficient during peak consumption periods during the winter.

Energy consumption coverage by onshore wind by region in 2023



Onshore wind production covers nearly 30% of the electricity consumption of the Hauts-de-France and Grand-Est regions, which are among the four largest consumers of electricity in France.

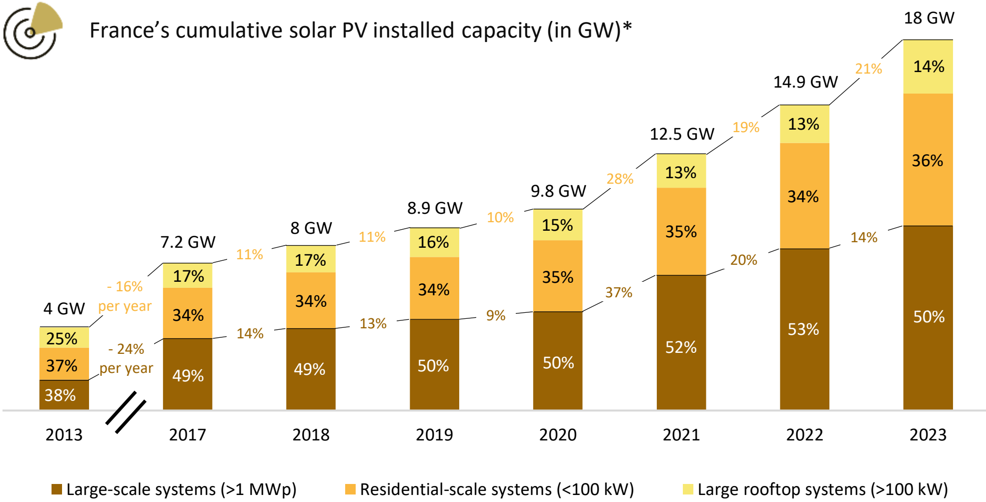
Sources: Agence ORE; Enedis; RTE

2.2

High-power solar PV

With over 3 GW installed in 2023, the solar PV sector has set a new growth record, bringing its cumulative installed capacity to 18 GW

France's cumulative solar PV installed capacity (in GW)*



- Of the 3.2 GWp connected in 2023, utility-scale systems (>1 MW) account for almost one third of new capacities.
- Between 2013 and 2023, the installed capacities of large installations increased sixfold, marking the largest growth in the PV sector.
- The installed capacities of residential and large rooftop installations have increased by a factor of 4 and 2.7, respectively.

1 Since 2020, grid connection trends have accelerated sharply, with an average growth of 23%, compared to 11% for 2017–2020.

2 Since 2017, the growth of the sector has been mainly driven by large systems, which represent 50% of installed capacity.

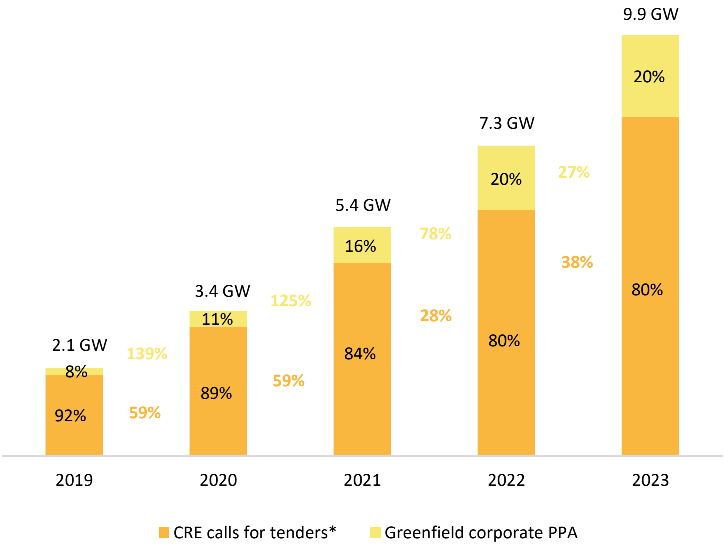
3 In 2023, a new record was set with 3.2 GWp of new capacities connected to the grid.

Sources: RTE; ENEDIS; ADEeF; CGDD-SOeS

ENEDIS data, excluding local distribution companies

In spite of the rise of PPAs, growth in the large-power PV sector (>1 MW) remains driven by CRE's calls for tenders

Cumulative PV capacity activated by the various support mechanisms since 2019 (in GW)



- Various support mechanisms are facilitating the development of high-power installations:
  - The public calls for tenders managed by the CRE
  - Corporate PPAs are long-term contracts that facilitate the direct purchase of renewable electricity between a producer and a consumer. These contracts require the buyer (offtaker) to purchase an amount of electricity that is generated by a specific renewable energy source at a predetermined rate for a specified period.
- In both instances, these mechanisms allow for locking in a fixed or indexed price for the sale of the generated electricity. This price is decorrelated from prices and fluctuations on the electricity market, depending instead on production costs:
- However, given the long duration of these contracts (15–20 years for greenfield CPPAs in France), securing them demands both parties (particularly the offtaker) to be financially very sound. Guarantee funds, like those backed by BPI France, are one solution to facilitate the widespread adoption of CPPA contracts for mid-sized buyers.

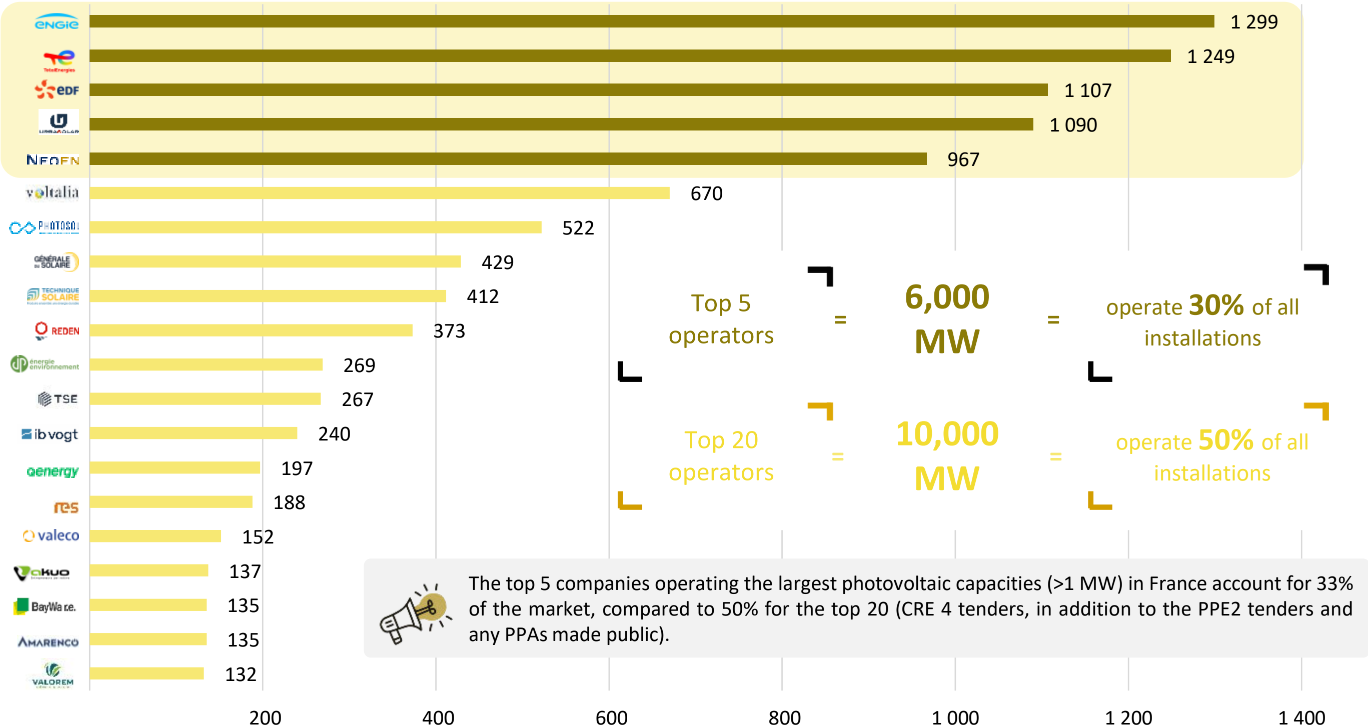
PPAs have experienced a growth rate that is **3 times** higher than that of calls for tenders between 2019 and 2023.
In total, the total capacity of installations with a unit production capacity of over 1 MW is estimated at 9.9 GW.

**CRE 4 and PPE2 (ISB and IAS) calls for tender for projects with capacities greater than 1 MW.*

Sources: French Ministry of Ecological Transition; CRE; Capgemini Invent

The high-power solar PV market is highly fragmented, with the 20 largest operators accounting for only 50% of the total capacities

Top 20 companies by solar PV capacities in operation in 2023 (in MW)



The top 5 companies operating the largest photovoltaic capacities (>1 MW) in France account for 33% of the market, compared to 50% for the top 20 (CRE 4 tenders, in addition to the PPE2 tenders and any PPAs made public).

Sources: French Ministry of Ecological Transition; CRE; Capgemini Invent

The market is highly dynamic and is characterized by new entrants and multiple acquisitions of companies or asset portfolios

New entrants are seeking to extract value from an attractive solar market

The dynamism of the solar market is fueled by support mechanisms and CPPAs and benefits from **lower barriers to entry than other renewable energies**, with:

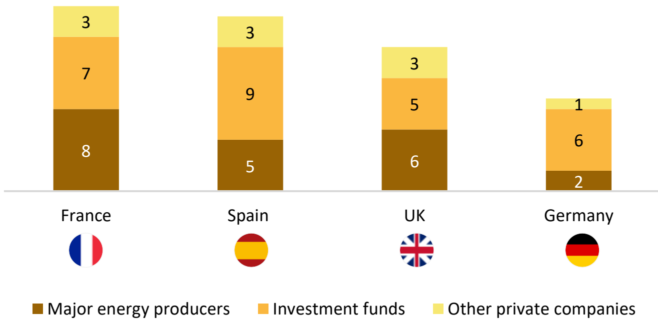
- Shorter project development time (4–5 years on average for solar PV vs. 10 years for wind),
- low initial investment requirements,
- technical ease of installation (simple structures).

3 Types of companies operating in the market

- France's two historical utility companies
- **Historical pure players** in renewable energies
- **New entrants**, whether pure players or companies outside the energy sector with significant land assets and/or financial resources (e.g.: SNCF Renouvelables

Market participants seeking to accelerate their development through external growth

Number of M&A transactions since 2019 by buyer type on the main European markets



SNCF Renouvelables

In July 2023, SNCF announced the establishment of a new subsidiary, SNCF Renouvelables, aimed at boosting its solar PV power production. SNCF has **invested €1 billion and dedicated holdings of 1,000 hectares** with the goal of producing 1 GW of energy by 2030, which would account for 15–20% of its energy consumption.

PHOTOSOL Producteur d'énergie solaire

The acquisition of Photosol by the French group Rubis in December 2021, valued at USD 844 million, signifies the diversification of its portfolio towards greater renewable energy investments.

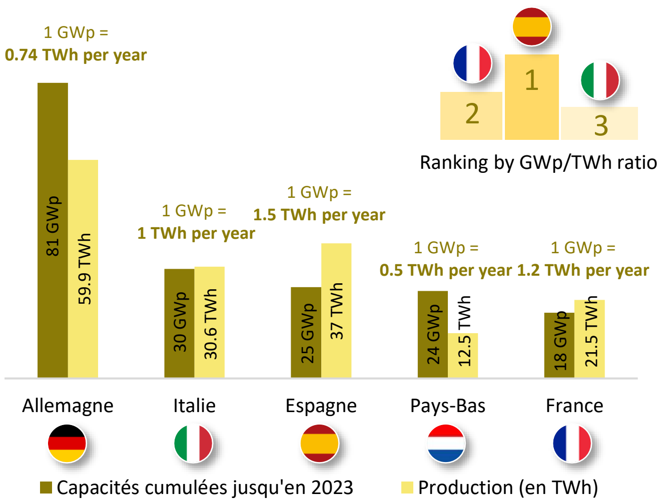
REDEN SOLAR

Macquarie's €2.5 billion acquisition of Reden Solar in 2022, marks the largest takeover of a solar company in Europe since 2019.

Sources: Enerdatics Energy Transition M&A database; Xerfi

Compared to other European countries, France has a high PV production in proportion to its installed capacities

Top 5 European countries by installed PV capacity (in GWp)



Compared to 2022, the development of photovoltaics has accelerated across European countries: in Spain (+28%), in France (+21%), in Germany (+20%), in Italy (+20%), and in the Netherlands (+24%). With 56 GWp of installed capacity in 2023, Europe's total installed capacity has increased from 207 GWp to 263 GWp, an increase of 27% in one year.

To accelerate the development of solar PV in Europe, the European Commission has presented the RePowerEU plan, which aims to achieve:

600 GWp

of installed capacities by 2030

To achieve this goal, the European Commission proposes making the installation of solar panels on new public, commercial, and residential buildings mandatory.

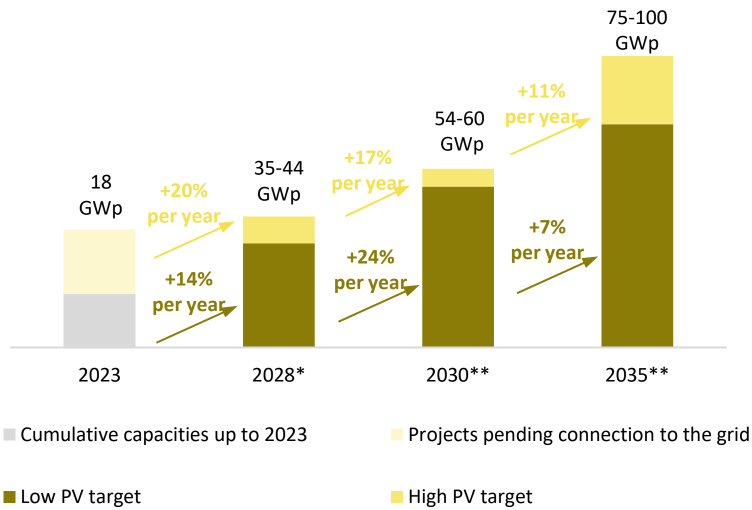
In 2023, France will be Europe's 2nd largest producer of electricity in proportion to its installed capacity (in GWp). For each operational GWp in France, 1.2 TWh is produced annually. In comparison, Germany has a relatively low annual solar power production in relation to its installed capacity (0.74 TWh generated per year for 81 GWp installed).

The IEA confirms that Europe's photovoltaic sector is set to double growth rate by 2028. Growth projections for the solar PV sector are significant, as it is expected ta account for almost 70% of new installed capacities in renewable energies by 2028 (followed by wind at 26%).

Sources: Bundesnetzagentur; Italia Solare; Red Eléctrica; Nationaal Solar Trendrapport 2023; RTE; EIA

To meet national objectives, the sector must sustain its pace of development for solar PV projects

Objectives for the development of solar PV capacity by 2035 (in GWp)



Adopted on March 10, 2023, the APER law on the acceleration of renewable energy production aims to intensify the development of the photovoltaic sector:

- It establishes a legal framework for agrivoltaics, which represents a major development opportunity given France's utilized agricultural area (UAA) of 28 million hectares.
- It mandates that all outdoor parking lots existing as of July 1, 2023, with a surface area greater than 1,500 m², must be equipped with photovoltaic canopies covering at least half of their area.

The installation of projects that do not meet the definition of agrivoltaics is significantly more restricted. One year after the law is enacted, solar installations will be prohibited in forest areas if they require clearing more than 25 hectares.

Since 2021, France's solar PV has experienced a record grid connection rate, with an annual growth of 20%, i.e., an average 2.8 GWp per year. To achieve the objectives set out in the 2028 PPE, France's installed capacity will have to continue growing at least 17% per year. **The "low" target could be achieved through the connection of queued capacities. To achieve this objective by 2035, France needs to connect an average of 4.8 GWp per year, equating to an average annual growth rate of 14%.

Sources: French Strategy for Energy and Climate (SFEC); PPE

**Objectives set by the PPE*
*** French Strategy for Energy and Climate*

In line with the European strategy, France is relaunching its photovoltaic module production industry

PV module manufacturing process

Silica extraction	Wafer production	Cell manufacturing	PV module assembly
Silica is extracted in quarries, primarily in the form of quartz. Good quality silica deposits are quite rare, but are present on all continents.	The silicon is molten in a furnace and then cast into lingots with a multicrystalline structure. These lingots are then sliced into wafers.	The wafers are further processed (dopant diffusion, passivation, coating deposition, metal inline printing) in order to produce solar cells.	The cells are strung together in modules, which are encapsulated between glass sheets and framed with aluminum.

Holosolis

IPCEI

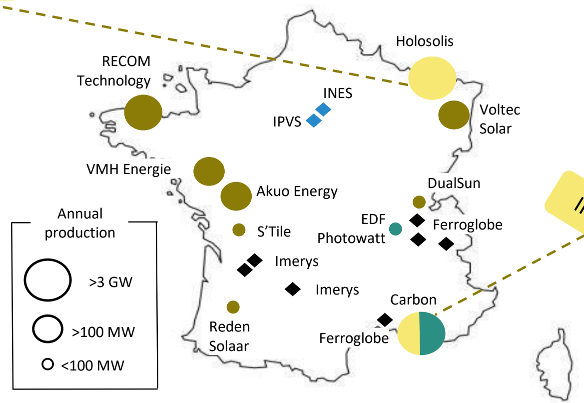
Sarreguemines-Hambach

€750 billion
Investment (CAPEX)

1900
Jobs in 2025

5GW
Module production in 2025

Geographic distribution of production facilities



CARBON

IPCEI

Fos-sur-Mer

€1.5 billion
Investment (CAPEX)

3000
Jobs in 2025

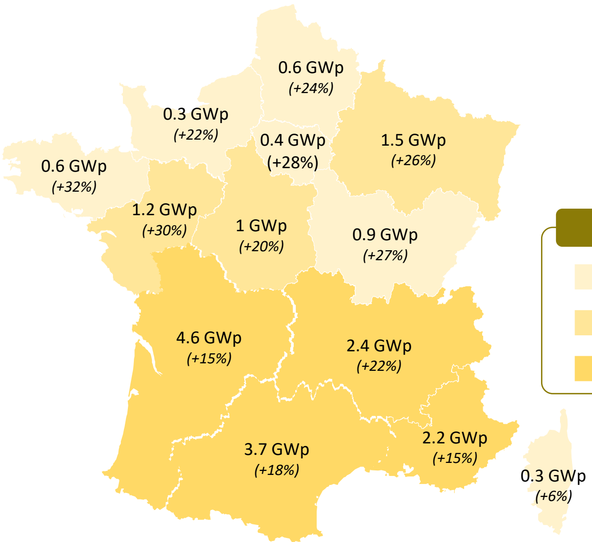
5GW
Module production in 2025

- ● Module production facilities
- ◆ Silicon production plants
- ● *Projected* module production facilities
- ◆ Research and training institutes
- ● Wafer production facilities

Sources: CNRS; ENGIE

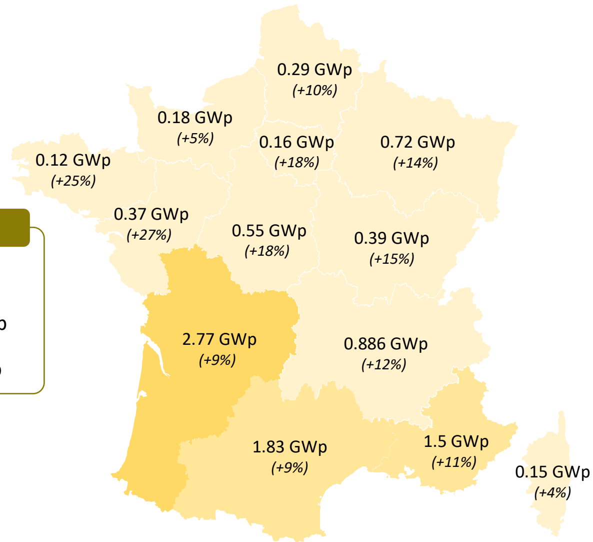
As of 2023, installed photovoltaic capacities are unevenly distributed across metropolitan France

Regional distribution of solar PV installations in 2023
(Solar PV, all capacities)



Capacity in GWp
- < 1 GWp
- 1–2 GWp
- > 2 GWp

Regional distribution of solar PV installations in 2023
(Utility-grade solar PV, >1 MWc)



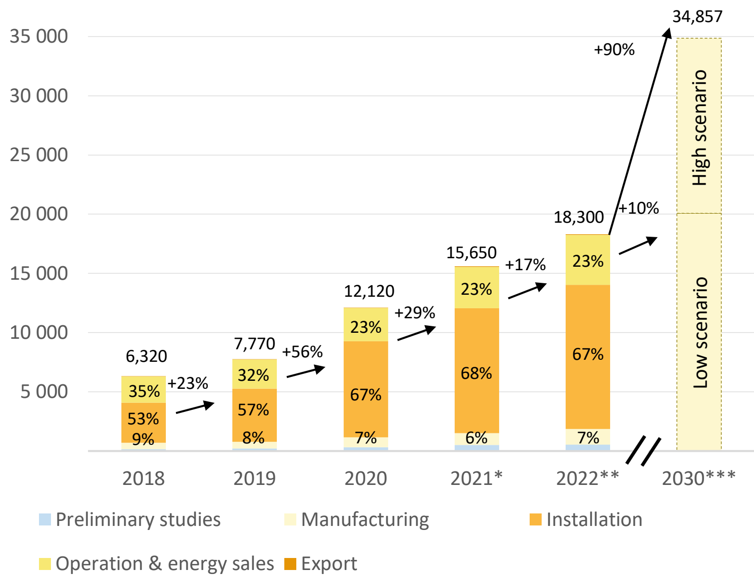
40% of metropolitan France's solar PV total capacity is concentrated in the Nouvelle-Aquitaine (22%) and Occitanie (18%) regions. Regions with lower installed capacity (in northern France) are experiencing higher growth rates (+20%).

The Nouvelle-Aquitaine and Occitanie regions account for nearly 45% of installed capacity. Western parts of the country are experiencing the highest growth for utility-scale solar PV farms (+20%).

Sources: ODRE; ENEDIS

The growth of the solar PV sector is generating tensions in the job market

Breakdown in solar PV jobs by link in the value chain (FTEs)



- The number of jobs in solar PV **increased 2.5-fold** between 2018 and 2022. 91% of solar jobs are concentrated in one of two links in the value chain: installation (68%) and operations & energy sales (23%).
- Projections from the French Electricity Union (UFE) indicate that the number of jobs in the sector could amount to 20,073–34,787 FTEs by 2030, which would be **double the total number of solar jobs in 2022**.
- Certain professions are in short supply, leading to recruitment challenges, particularly for **project managers and electrical technicians**. To meet market demand, companies are **implementing academic and professional training programs** within their organizations. For instance, DualSun is training 500 installers each year.

**Semi-final results*
***Provisional results*
****Projections from the French Electricity Union (UFE)*

Sources: ADEME; UFE

Agrivoltaics is a significant growth driver for achieving the objectives set by the SFEC

The need for land for large photovoltaic installations is increasingly challenging the sector's development, particularly in the context of preventing soil artificialization and preserving biodiversity, especially with the "zero net artificialization" goal.
As a result, it is necessary to scale up solar PV production practices. With its agricultural area of 26 million hectares, agrivoltaics presents significant growth opportunities for France.

A definition of agrivoltaics

"electricity production installation that uses radiative solar energy and whose modules are located on an agricultural parcel where they contribute sustainably to the installation, maintenance or development of agricultural production."

Article 54 of the APER Law on accelerating the production of renewable energies

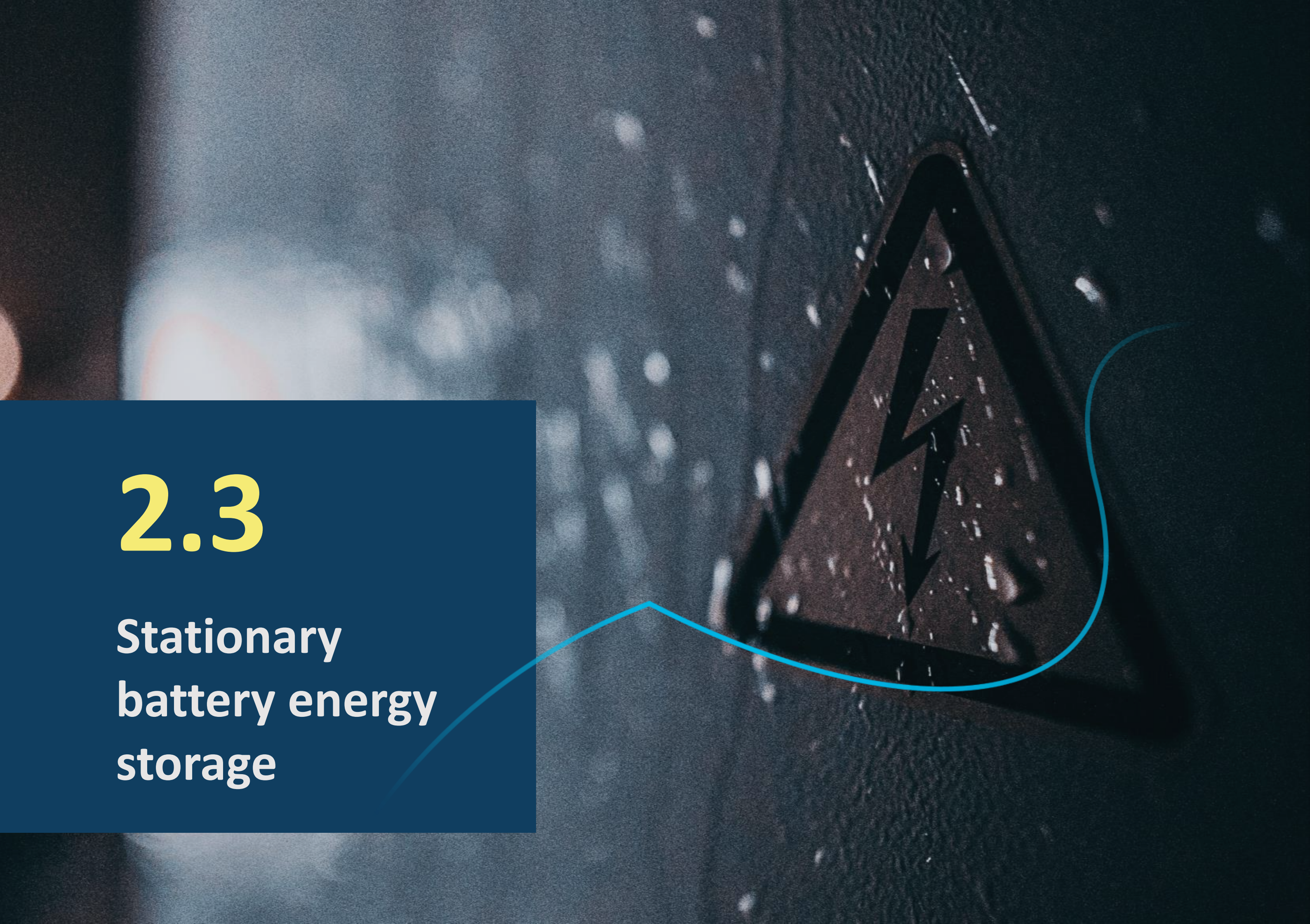
Published in the Official Journal on April 9, 2024, the implementing decree specifies a series of controls and sanctions applicable to agrivoltaic installations in its Article 6. In the long term, it is necessary to ensure that photovoltaic installations are compatible with agricultural activities, which is why the implementing decree includes a program for monitoring dismantling operations. If it is established that the installation is no longer operational or that the conditions for compatibility with agricultural activities are no longer met, the project may be required to be dismantled.

150 GW

With 1% of its UAA covered by agrivoltaics, France could achieve 10 times its cumulative installed capacity of 2022, reaching 150 GWp. This would amount to 10 times more energy production than biofuels.

Compared to other European countries, France has the largest agrivoltaic potential, ahead of Spain (100 GW) and Italy (75 GW).. If this unexploited resource were integrated into the electricity grid, it could enable France to meet its solar PV target of 100 GW for 2050 immediately.

Sources: European Commission; JOUE

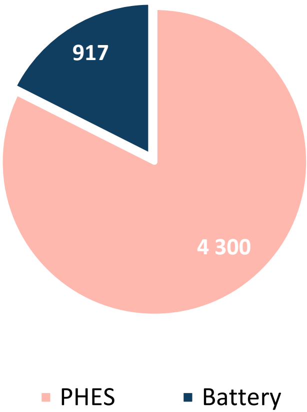


2.3

Stationary battery energy storage

The installed capacities of stationary battery storage are low compared to the historically developed PHES systems

Storage capacity in France expressed in MW in 2023



The resilience of the French system and the role of storage

- 75% of France's electricity is generated by highly flexible sources—nuclear and hydropower. There is currently 4 GW of pumped hydroelectric energy storage (PHES) capacity in place.
- This electricity mix has so far maintained the robustness and controllability of the electrical system while minimizing the need for extensive stationary battery storage.
- The role of storage assets is primarily, but not exclusively, to **store excess production and balance production shortages**, thereby helping to maintain the stability of the electricity system in response to fluctuations in consumption and production.

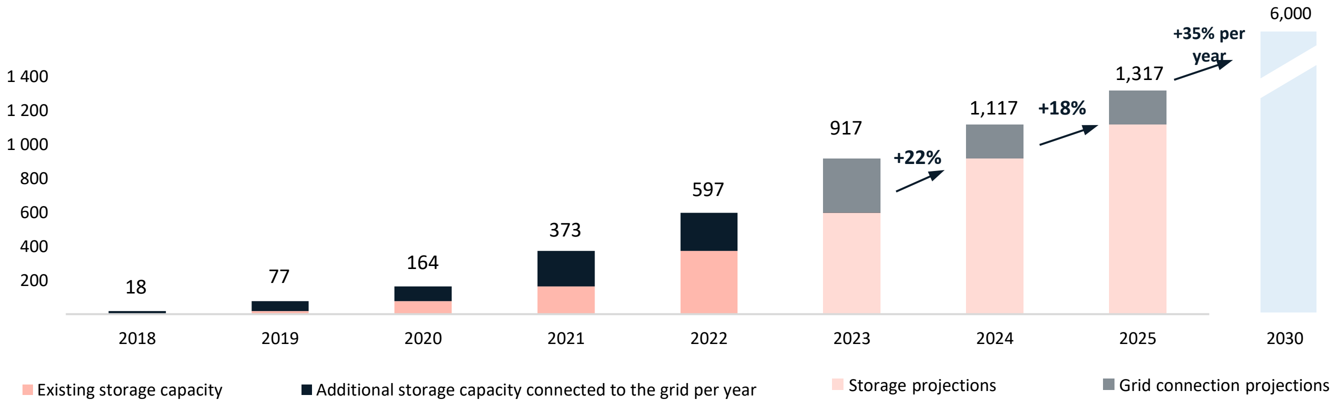
The rise in the share of renewable energies in the electricity mix (projected to reach 300 TWh in 2035 compared to 120 TWh in 2023) will heighten the need for stationary storage capacity due to increased production variability.

As potential PHES capacity is almost fully achieved, the need for stationary battery storage capacities will increase sharply in the coming years.

Sources: RTE; Xerfi "Les défis du marché du stockage de l'énergie" [The challenges of the energy storage market]

Stationary battery storage has been experiencing strong growth in recent years, and this trend is expected to persist

Storage power capacity in France (in MW)



Battery

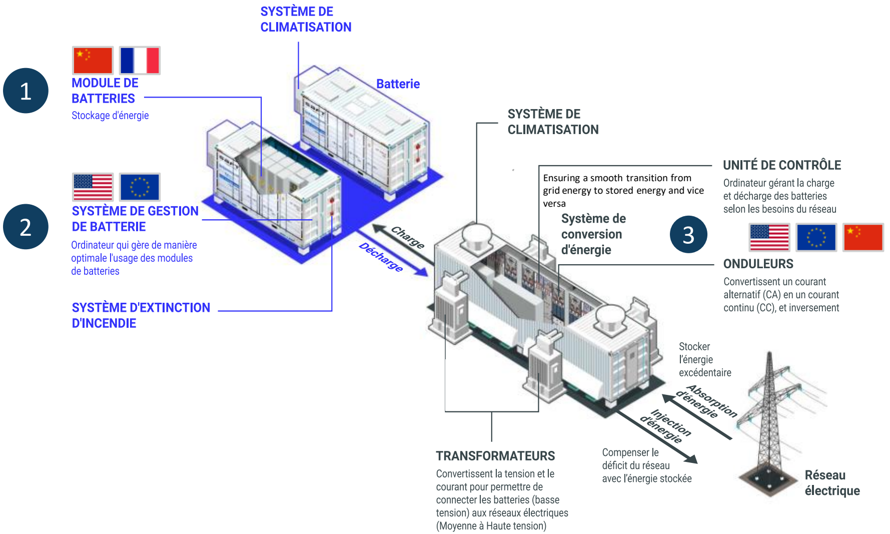
- **Rapid response** to fluctuations in demand
- **Obviates the need for heavy investments** required to strengthen the distribution network
- Offers an **efficiency bordering on 90%**
- Frees up spinning reserves for production
- Provides **short-term** storage: on an "intraday" basis
- Requires **critical metals** and raw materials

PHES

- Provides **long-term storage** (of several weeks)
- Allows for **high-power capacity**
- Offers an **efficiency of around 80%**
- **High CAPEX** requirements for installation and connection to the grid
- High **environmental impact**
- Requires a **stock of water** and favorable hydrological conditions

Sources: LCP Delta; French Senate; EDF

Understanding the structure and components of battery storage unit



€650k

per MW

of one-hour capacity batteries

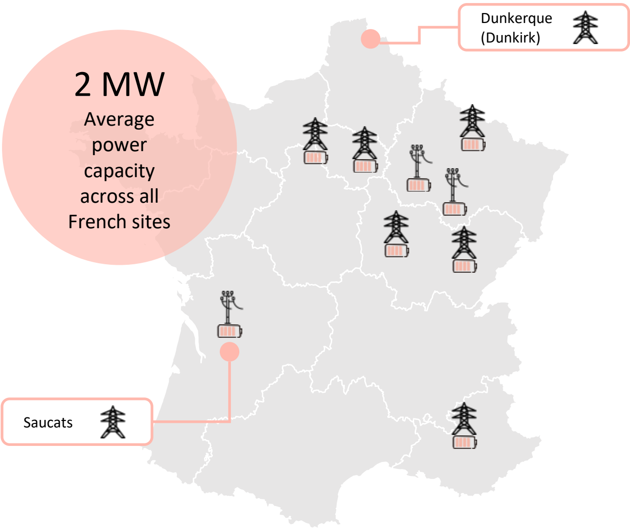
The three key components that constitute a stationary battery storage unit are:

1. The battery module will store electrical energy in chemical form. The primary raw material used in this component is **lithium.**
2. The battery management system (BMS) responsible for controlling the charging and discharging of battery modules.
3. The energy conversion system consists of transformers responsible for adjusting the electrical voltage level and inverters responsible for converting the direct current coming from the battery module into alternating current to be delivered to the network.

Sources: Le Monde; France Renouvelables analysis

Large-scale projects are emerging across the country, contributing to the acceleration of installed capacity growth

Battery storage site in Metropolitan France
(> 10 MW)



Battery storage sites in operation

Connection to the transmission network

Connection to the distribution network

Dunkerque (Dunkirk)

- Commissioning in two stages:
  in 2020, then in December 2021
- 61 MW, a project selected as part of the 2020 long-term tender
- Lithium-ion technology
- Approx. €40 million (extrapolating the €15 million of the 1st 25 MW tranche in 2020), i.e. €650k per MW
- Capable of maintaining power supply to 200,000 homes for one hour

Saucats 2

- Commissioned in late 2023
- 105 MW, including 75 MW benefiting from the long-term tender (AOLT) and a price locked in for 7 years
- Lithium-ion technology
- Approx. €56 million, i.e., €530k per MW
- Turnover: approx. €8 million per year
- 20 years minimum

Sources: Open Data Energy as of Dec 31, 2023; France Renouvelables; TotalEnergies; Amarenco

The market primarily attracts players from other industries, including renewable energy developers

Value chain stage	Players
Extraction of raw materials	Imerys
Cell and battery manufacturing	Verkor, Saft, Forsee Power, Blue Solutions, Tiamat, Kemwatt (new entrant), Equans (new entrant), Renault
System integrators, design and manufacturing of battery storage units	NW Group, Akuo, Agregio, Omexom, Socomec, Entech
Development and applications	Amarenco, Engie, TotalEnergies, Boralex, Neoen, Qenergy, EDF, NW Group, Innergex, Voltalia
Recycling	Orano, Veolia, Suez, Eramet

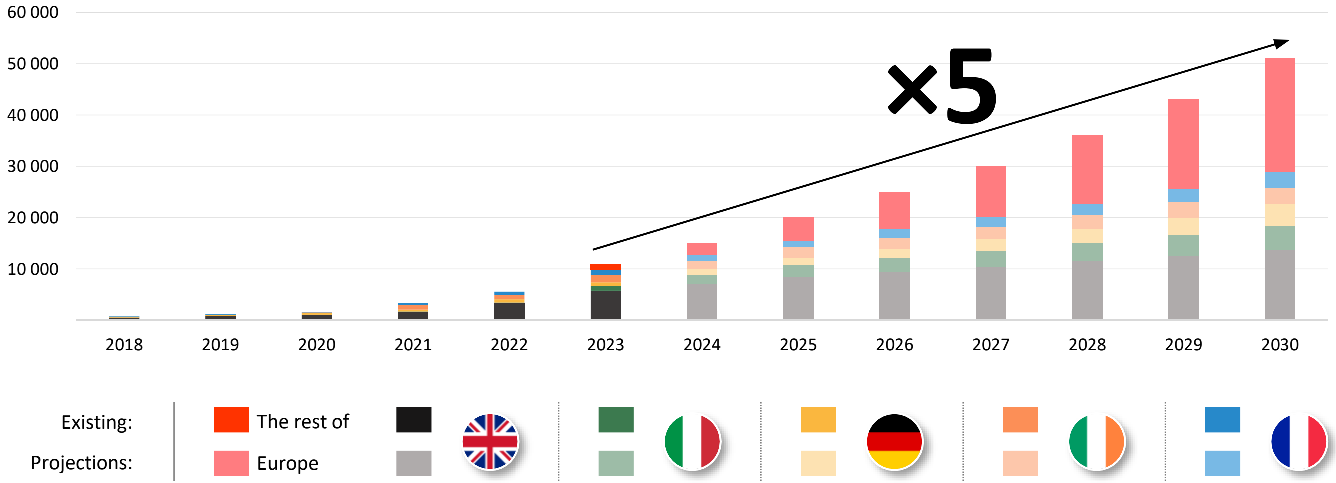
Developers and operators have diversified into storage to enhance the integration of renewable energies into the grid.

(new entrant) New entrants to the market

Source: France Renouvelables analysis

Installed capacity should increase threefold in France by 2030, which is a less pronounced growth compared to the European average

Installed and projected power capacity in different countries (in MW)

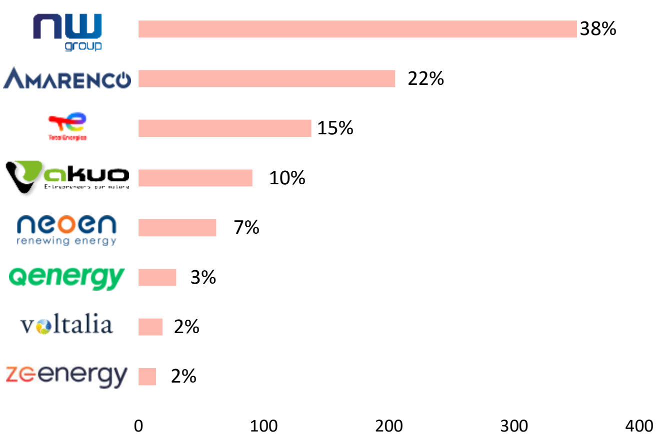


- **Installed capacity in Europe is projected to increase fivefold by 2030**, primarily driven by growth in Great Britain and, to a lesser extent, by Germany and Italy.
- This “British predominance” can be attributed in part to the following factors: the limited interconnection of its electricity system with the continent, its low potential for pumped hydroelectric storage (PHES), and substantial growth in wind production, which creates a strong need for battery storage capacity.

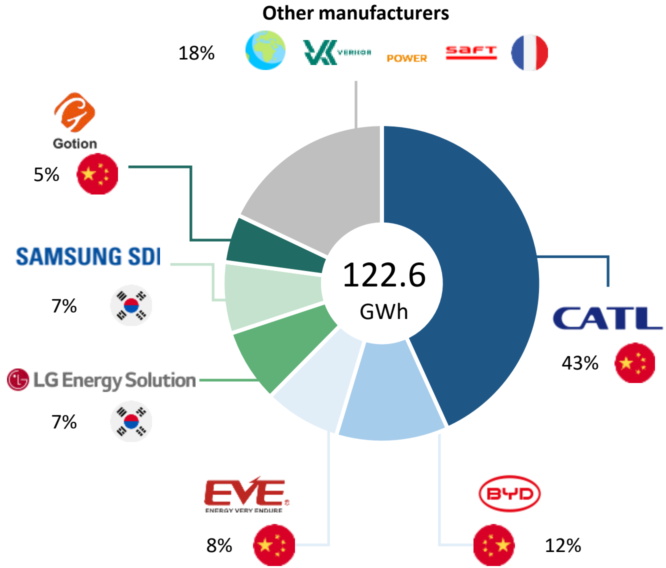
Sources: EASE; France Renouvelables analysis

Despite a concentrated market, the emergence of new French players signifies a shift in the competitive landscape.

Major battery storage site operators in France in 2022 (in MW)



Breakdown of the global battery production market in GWh for 2022



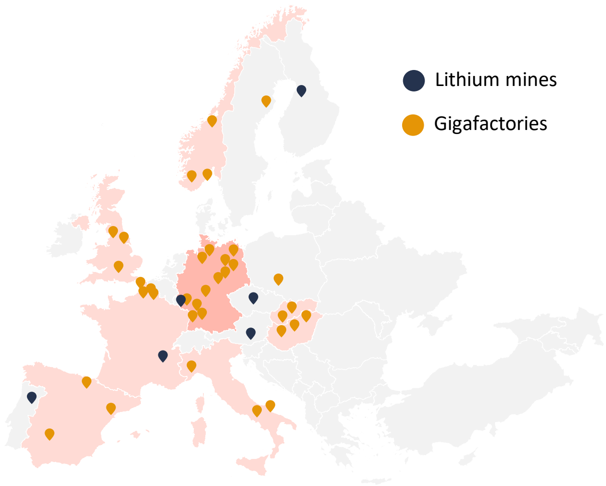
- The operation of storage sites in France is highly concentrated among a few key players.
- In 2022, 3 companies operate 75% of the installed capacity.

- 6 Asian companies dominate 80% of the storage battery production market.
- European players are nevertheless starting to emerge, buoyed by the demands of the electric mobility industry.

Sources: Statista; France Renouvelables analysis

A European and French industrial production system is taking shape around gigafactories and lithium mines to ensure supply security

Many projects are emerging in Europe



Germany hosts a significant number of Europe's battery gigafactories. Nonetheless, a "battery valley" is emerging in Hauts-de-France, featuring players like Verkor and ACC. These French gigafactories will supply both the automotive market and the stationary storage market.

VERKOR

Electric battery gigafactory in Dunkirk/Dunkerque

16 GWh
including 15 GWh that benefit from a long-term tender (AOLT) with a rate that is locked in for 7 years

3/4
of production is purchased by Renault

€1.5 billion
invested

2000
jobs

IMERYS

Emili Project, a lithium mine in Auvergne-Rhône-Alpes

34 kt
of hydrogen produced per year – over a 25-year operation

2nd
largest mine in Europe

€1 billion
invested

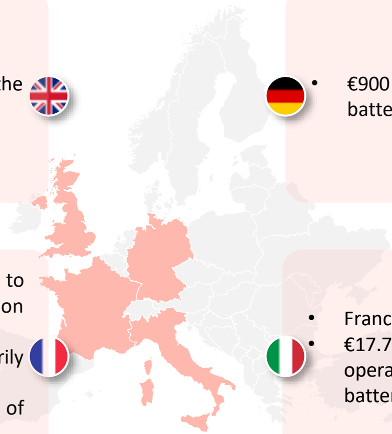
600
direct jobs

Sources: Statista; France Renouvelables analysis

Like the United Kingdom, France must establish a clear vision and objectives to reassure stakeholders in the sector.

The EU Strategic Action Plan on Batteries

- The European Battery Alliance was created with the aim of achieving strategic autonomy in the battery sector. The aim is to **establish a value chain for batteries in Europe**.
- The "European Battery Innovation" project (2019–2031), an IPCEI (Important Project of Common European Interest), allocates a total of €3.2 billion in public aid to promote research and innovation across all stages of the battery value chain.
- Support mechanisms are primarily focused upstream in the value chain, aiming to stimulate battery production. They will mainly benefit mobility, both in France and in Germany.



United Kingdom:

- 20 GW target by 2035
- Comprehensive €2 billion plan to strengthen the battery value chain
- €11 million in funding for 20 technology start-ups

Germany:

- €900 million subsidy for the establishment of a battery factory

France:

- France's **Batteries Plan was launched in 2018** to accelerate the emergence of a battery production chain
- **€903 million** in aid under the IPCEIs, primarily dedicated to electric vehicle batteries
- **38 battery-related projects** supported, for a total of **€233 million**

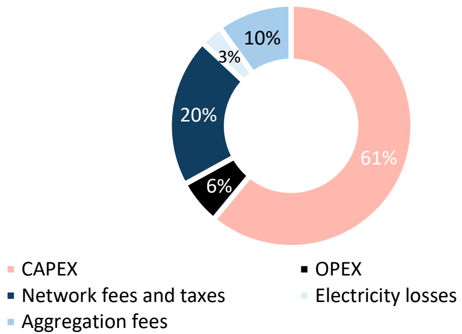
Italy:

- France's recovery and resilience plan (PNNR)
- €17.7 billion to support the construction and operation of a centralized pumped hydroelectric and battery energy storage system (PHES & BESS)

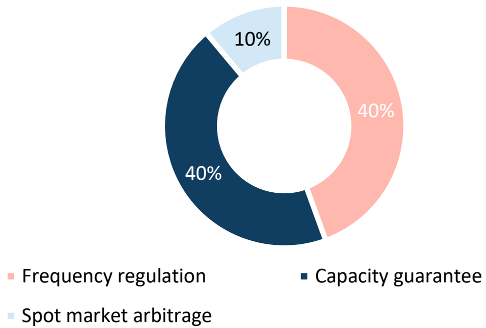
Sources: European Commission; French Ministry of Economics; France Renouvelables analysis

Improving revenue visibility is needed to unlock funding for CAPEX-intensive projects

Cost breakdown for a battery storage site (%)



Main sources of revenues for a storage site in France (%)



Difficulties in funding projects

- A CAPEX-intensive market that requires securing revenues over the long term to make initial investments profitable
- Financing conditions are tightening as interest rates increase

Income uncertainty

- The selection of bids for the provision of the primary reserve and the adjustment offers (frequency regulation) occur on a weekly and daily basis, respectively.
- The capacity mechanism provides visibility over one year. The long-term tenders (AOLT) have extended this duration to 7 years by guaranteeing the price of capacity certificates.
- Market arbitrage is subject to unpredictable market fluctuations and it is impossible to stack different revenue streams.

Sources: CRE; France Renouvelables analysis

New calls for tenders tailored to the specific needs of storage should be implemented

Past long-term tenders

Long-term tenders organized by RTE in 2019

7 years	€28–29k per MW	250 MW
Duration of the guaranteed price for the capacity certificates*	Guaranteed price for the capacity certificates	Winning storage capacity

Revising connection procedures to account for the specificities of battery storage would accelerate the sector's development.

2020-2026	2021-2027
No project selected	91 MW battery for a capacity certificate price locked in at €29k per MW over 7 years
2022-2028	**2023-2029**
60 MW battery for a capacity certificate price locked in at €29k per MW over 7 years	No project selected

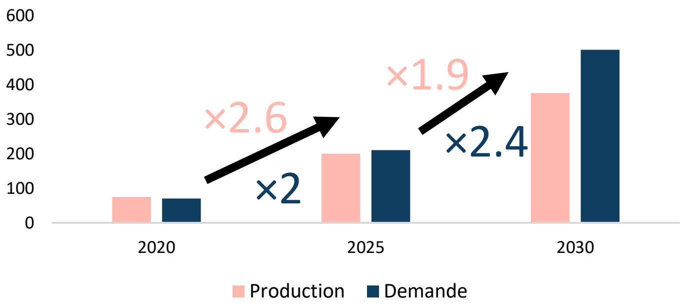
Developments required to support the sector

- Ensuring that existing price signals accurately reflect the true value of the various services provided by the installations, balancing the electricity system, and minimizing the need for investments to reinforce the distribution network.
- Establishing long-term remuneration mechanisms that ensure the viability of the installations' business models and allow for the stacking of multiple revenue streams
- With the primary frequency regulation service becoming saturated, exploring new markets is essential to sustain the development of storage
- Battery storage should be regarded and treated as a network asset

Sources: RTE; CRE; France Renouvelables analysis

New battery technologies must be explored to limit lithium dependence and mitigate supply risks

Analysis of global lithium production and demand (kt)



- An imbalance between lithium demand and production is expected from 2025, increasing until 2030, and resulting in supply tensions.
- **Electric mobility and stationary battery storage are competing** for access to lithium-ion batteries
- Alternative technologies that are not reliant on lithium, such as sodium-ion, along with a “second-hand” market for batteries, should be explored to ensure the future of stationary battery storage.

Securing supply sources

The Critical Raw Materials Act (CRMA), with the aim of strengthening the EU’s competitiveness and sovereignty

Securing supplies:

- By relocating raw material extraction to Europe can reduce dependence on specific countries and enhance the security and stability of supply.
- By diversifying our supplier countries, we can secure our supply chains and reduce the risks associated with over-dependence

Sources: AIE; OFREMI; France Renouvelables analysis

2.4

Low-carbon hydrogen

Low-carbon hydrogen is a valuable asset for the energy transition

One of the primary applications of hydrogen is the production of ammonia and as a feedstock for many processes in chemical manufacturing and oil refining.

There are various methods used to produce hydrogen:*

Carbon-intensive hydrogen | 11 kg CO_2e per kg H_2 (94%)		Low-carbon hydrogen | 0.6–3.2 kg CO_2e per kg H_2 (6%)		Native hydrogen
Gray hydrogen	**Blue hydrogen**	**Yellow hydrogen**	**Green hydrogen**	**White hydrogen**
Produced from fossil hydrocarbon sources, primarily via steam methane reforming.	Produced from fossil hydrocarbon sources, but using a carbon capture and storage (CCS) technology.	Produced via electrolysis, primarily using nuclear power.	Produced via electrolysis, using renewable electricity.	Naturally occurring hydrogen that isn't produced through the transformation of natural gas or electrolysis.

Renewable hydrogen is beneficial for decarbonizing industry and mobility and accelerating the development of renewable sources of electric power

Decarbonizing mobility and industry

1 In the transport sector, hydrogen vehicles emit less than 15 t CO_2 vs. 45 t for internal combustion vehicles. In the industry, low-carbon hydrogen can also contribute to reducing emissions, as 90% of hydrogen that is currently used is derived from fossil fuels.

Storage

2 Electrolysis enables the storage of hydrogen during periods of electricity surplus on the grid. It can later be used in fuel cells and thus provide flexibility to the electrical system during periods of peak demand.

Mass production

3 The challenge is to produce renewable hydrogen on a massive scale to meet decarbonization objectives. To achieve this, an increase in the production of electricity from renewable sources is required to power the electrolyzers.

**The percentages indicate the share in global hydrogen production*

With 30 MW of cumulative production capacity at the end of 2023, the low-carbon hydrogen sector is still in its infancy.

Hydrogen is mainly produced using fossil fuels

30 MW

Cumulative installed production of low-carbon hydrogen

6%

Share of low-carbon hydrogen in total production

Low capacity projects and a sector concentrated among a limited number of businesses

1.5 - 2 MW

Average capacity of low-carbon hydrogen projects

70%

of operating capacities are managed by 4 industrial players

Production costs remain high

×4

The cost of producing low-carbon hydrogen compared to gray hydrogen under optimal conditions (alkaline electrolyzer; 4,000 hours of annual use; a price of renewable electricity of €75 per MWh thanks to a PPA)

A sector that is dependent on support mechanisms

€500 million

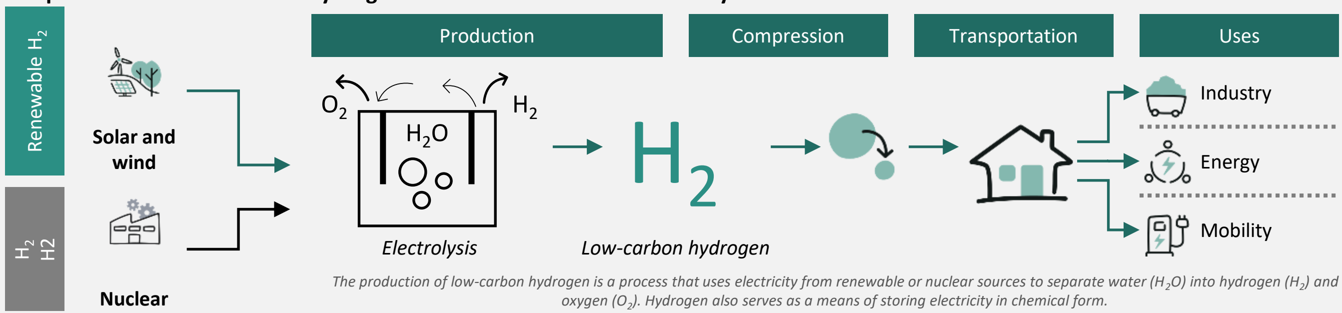
State support for low-carbon hydrogen infrastructure projects

A technology still in its maturation phase

70%

Share of “alkaline” electrolyzers, a technology that has low efficiency compared to other technologies that are, however, still not very mature.

The production of low-carbon hydrogen is carried out via water electrolysis



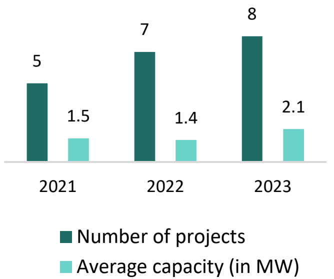
The production of low-carbon hydrogen is a process that uses electricity from renewable or nuclear sources to separate water (H_2O) into hydrogen (H_2) and oxygen (O_2). Hydrogen also serves as a means of storing electricity in chemical form.

Source: IFP Énergies Nouvelles

The sector is concentrated around a few players and mid-sized projects

Project size

Changes in the number of new projects and average capacity (in MW)

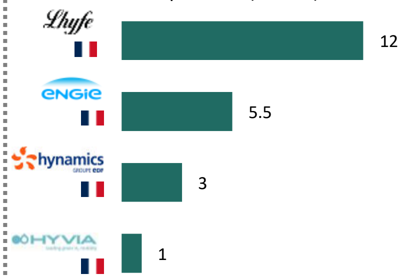


On average, production infrastructure projects use electrolyzers with capacities of around 1.5–2 MW.

In 2023, the average size of projects brought online exceeded 2 MW.

Top operators

Breakdown of installed production capacities in operation (in MW)

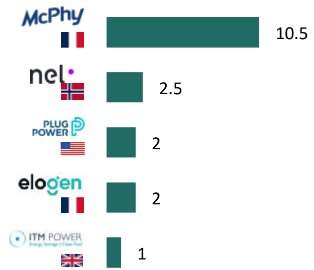


The market for the production of low-carbon hydrogen is highly concentrated. **4 companies account for 70%** of the installed capacity. Traditional energy companies (EDF, Engie) are already positioned, particularly through dedicated subsidiaries.

The market is nevertheless attracting new specialist players like Lhyfe, which is France's top low-carbon hydrogen producer.

Top electrolyzer suppliers

Breakdown of installed production capacities in operation (in MW)



The market for manufacturing and supplying electrolyzers is **highly concentrated**. **4 companies account for 60%** of the installed capacity.

McPhy alone represents one third of installed production capacities.

Source: Capgemini Invent analysis

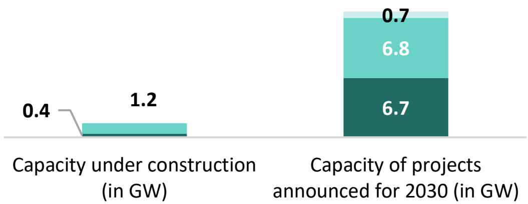
The value chain is increasingly structured around multidisciplinary developers

Category	Country	Company	Development and engineering	Equipment manufacturing	Procurement & Construction	Operations & Maintenance	Storage & Distribution	Applications	Production of renewable electricity
Developers, operators, and distributors	France	Lhyfe	●		●	●	●		
	France	Engie	●		●	●	●		●
	France	Hynamics	●		●	●			
	France	Air Liquide	●		●	●	●		
	France	INTHY	●		●	●	●	●	
	France	Valeco	●		●	●	●		●
	France	Qair	●		●	●			●
	France	TotalEnergies					●		●
	France	Storengy					●		
	France	Equans			●				
	Germany	Siemens Energy	●	●	●	●			
	Germany	Enertrag	●		●	●			●
Manufacturers of equipment related to hydrogen production, storage, or applications	France	McPhy		●					
	Belgium	John Cockerill		●		●			
	France	Elogen		●					
	France	Symbio		●					
	France	Hysetco		●				●	
Transporters	France	GRDF					●	●	
	France	Teréga					●		
	France	GRTgaz					●		

- The sector is structured around companies operating across a significant portion of the value chain, from development to distribution, including the construction and operation of production facilities. Other companies, primarily international, specialize in manufacturing equipment related to hydrogen production, storage, or utilization, such as electrolyzers, and charging stations.
- France's historic operators of gas storage, transport and distribution networks are working to adapt the network and operating methods to allow for the injection of low-carbon hydrogen.

Technologies continue to evolve, improving efficiency, enhancing flexibility, and driving down costs

70% of the capacity under construction in Europe relies on alkaline technologies, which have relatively low efficiency.



Scaling up the production of low-carbon hydrogen requires the use of high-performance electrolyzers

- Due to their technological maturity and low cost, alkaline technologies dominate the market in Europe, accounting for 70% of new capacities under construction.
- The Proton Exchange Membrane (PEM) technology, which offers higher conversion efficiency than alkaline technology, is currently experiencing a growth phase. Both more modular and more flexible, PEM can absorb a higher current density and can operate with variable load levels. Its share is expected to double to almost 50% by 2030.
- In the context of electricity production from renewable sources and the need for greater flexibility in the electricity grid, investing in electrolyzers that can adapt to the load variability of different renewable energy sources is essential.

	Alkaline electrolysis cell (AEC)	Proton exchange membrane (PEM)	Solid oxide electrolysis cell (SOEC)
Maturity	+++	++	+
Yield	60% - 65%	77%	85%
Benefits	Alkaline technology has the advantage of using inexpensive catalysts.	PEM systems are more compact and capable of effectively handling the variability of electricity loads from various renewable sources.	SOEC (solid oxide electrolyzer cell) systems are high-efficiency (up to 85%) and hold significant potential for higher sustainability in hydrogen production.
Disadvantages	Their cells cannot operate under high pressure and take up a lot of space, however.	PEM electrolyzers are more expensive because of the materials used for the stacks.	Due to the high temperatures and special ceramic materials involved, SOEC electrolyzers are complex and expensive to manufacture.

Source: Hydrogen Europe

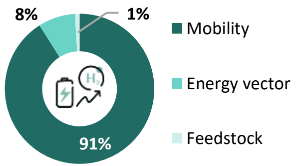
State support mechanisms will evolve to accelerate the sector's development.

The French state has defined a budget of €9 billion by 2030 as part of its national strategy for the development of low-carbon hydrogen. Of this total, €3.4 billion have been allocated for investment support (CAPEX) over the 2020–2023 period, and an additional €4 billion will be made available for production support from 2024 to 2026.

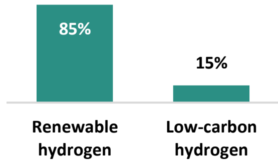
The French state has already financed investments in low-carbon hydrogen infrastructure to the tune of €500 million

- The French state has financed the construction of around 50 industrial projects to the tune of €320 million **through ADEME's EcosysH$_2$ calls for projects**. ADEME's contribution accounts for **26% of total investments, amounting to €1.2 billion**. In May 2023, an additional allocation of €175 million was made available to finance new projects.
- These fundings have primarily targeted mobility projects (91%), leveraging **grid-connected** electrolyzers, and using renewable electricity (85%) with guarantees of origin supplied through **CPPA-type supply contracts**.

Use of hydrogen in winning projects (in project volume)*



Type of hydrogen in winning projects*



A new allocation of €4 billion will be mobilized to support production

A new call for projects mechanism will help lock in the sale price of hydrogen for a capacity of nearly 1 GW over the next three years.

150 MW (2024) → **200 MW** (2025) → **600 MW** (2026)

Since January 1, 2023, renewable hydrogen has been integrated in the TIRUERT, an incentive tax related to the use of renewable energy in transport that has been renewed annually in the state budget. As of January 1, 2024, low-carbon hydrogen is eligible for incentives of up to €4.7 per kg. In 2024, the renewable energy incorporation rate is 9.9% (compared to 9.5% in 2023).

**Projects identified in ADEME's 2018–2020 report*

Source: ADEME

France has strong ambitions: 6.5 GW of installed production capacity in 2030 to decarbonize the industrial sector as a priority

Europe sets the course for the production of renewable hydrogen…

The European Commission has launched the Hydrogen for Climate Action plan which aims to replace fossil fuels with low-carbon hydrogen (RFNBO) and is requiring member states to set ambitious objectives:

40 GW
Installed electrolyzer capacity in 2030

€470 billion
Total investments in renewable hydrogen in 2050

…and implements a regulatory framework to accelerate the decarbonization of industry on a European scale.

The EU's 3rd Renewable Energy Directive (RED III) sets targets for the use of renewable hydrogen in industry and transport, which will key drivers of hydrogen demand.

40%
Use of renewable hydrogen in industry in 2030

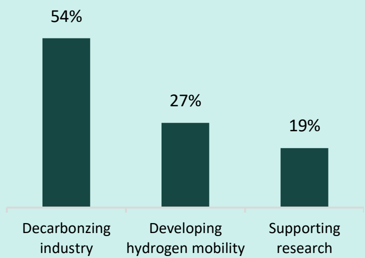
1%
Use of low-carbon hydrogen in transport in 2030

France has adopted an ambitious strategy* to achieve 6.5 GW of low carbon H2 production by 2030

France is implementing a three-pronged hydrogen deployment roadmap:

1. Decarbonizing industry by helping a French electrolysis sector emerge
2. Developing heavy mobility using low-carbon hydrogen
3. Supporting research, innovation, and skills development

Breakdown of the €3.4 billion based on the French state's priority areas



Carbon-fee hydrogen production targets

6.5 GW
Low-carbon hydrogen capacity: ambition for 2030

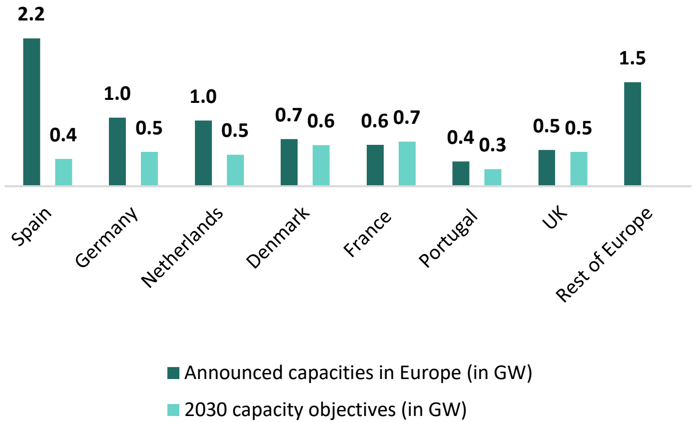
10 GW
Low-carbon hydrogen capacity: ambition for 2035

**Strategy currently under review*

Sources: Hydrogen for Climate Action; France's national strategy for the development of low-carbon hydrogen; Low-carbon roll-out plan

This ambition positions France among the top five European countries in the development of the hydrogen sector

The projects announced by European countries for 2030 will allow them to meet their capacity targets.



Uneven progress in electrolytic hydrogen production: China is leading, while Europe and France are still in development

- With 6 GW of projects announced, France is close to its objective. However, it still lags behind **Spain, Germany, the Netherlands, and Denmark**, which have accumulated 22, 10, 10 and 7 GW of announced capacities, respectively.
- At the European level, the announced capacities for 2030 already meet the planned objectives.
- Despite these ambitious European objectives, China remains the undisputed market leader. In 2022, China installed 200 MW of new generation capacity, including the largest project in the world, which has a capacity of 15 MW. According to IEA projections for 2023, China has more 1 GW of cumulative production capacity, thus accounting for 50% of global installed capacity.

Key success factors for hydrogen

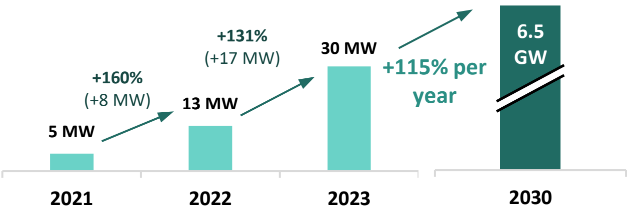
The challenge for France, like its European neighbors, is to accelerate development and commissioning to ensure that these announced projects come to fruition within the planned time frame. To achieve this, it is necessary to **eliminate obstacles and address the challenges facing the sector**

Source: IEA

France is building an industrial ecosystem capable of increasing the rate of installation of new capacities

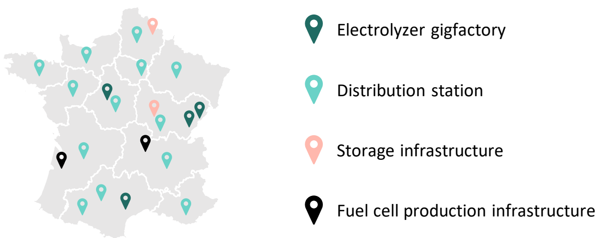
France must double its installed capacity, each year, until 2030:

Evolution and growth of installed capacities (in GW)



France must create synergies between the various industrial ecosystems in the sector:

Geographical distribution of the various industrial ecosystems that are complementary to hydrogen production *(non-exhaustive map)**



Sources: Capgemini Invent analysis; Air Liquide

In order to achieve its 6.5 GW target for 2030, the French hydrogen sector must:

- Maintain an annual growth rate of 115% on the installation of new capacities.
- Gradually move towards utility-scale projects, transitioning to unit production capacities of around 10–20 MW to 50 MW and more. At current capacities of operating projects, France would need to develop 4,000 new projects within the next six years.
- Being able to produce at least 35–42 TWh of renewable electricity, amounting to almost 50% of the country's solar and wind power production in 2023.
- Ramping up the production of reliable components (electrolyzers) in a timely manner to benefit from economies of scale. The gradual increase in project size is expected to provide the industrial ecosystem with the learning curve needed to ultimately support "megaprojects"
- The development of the sector will be achieved by leveraging synergies with industrial ecosystems that are complementary to hydrogen. A second driving force for development is the formation of partnerships among various industrial players and the integration of start-ups as they scale up.

**Presented here: the four announced electrolyzer gigafactory projects, the largest hydrogen storage and fuel-cell production infrastructure, and hydrogen refueling stations scattered throughout the country.*

The sector must now accommodate large-scale projects focused on hydrogen and electrolyzer production

Today, the sector accommodates small-capacity projects on a local scale…

The HyGO project (a company founded by Engie and Morbihan Énergies) aims to produce green hydrogen via electrolysis (using renewable electricity supplied by Engie) for Michelin's industrial uses, as well as to supply a public hydrogen refueling station for light and heavy vehicles in the city of Vannes.

300 kg

Production of low-carbon hydrogen per day

Major projects with capacities exceeding 200 MW will come to fruition…

The Normand'HY project initiated by a joint venture between Siemens Energy and Air Liquide will begin operations in 2026. At full capacity, it will produce 28,000 tons of green hydrogen per year for industry and mobility using a PEM technology. The Saint-Jean-de-Folleville site was selected because it accounts for 13% of France's industrial CO2 emissions.

200 MW

Installed electrolyzer capacity in 2026

While gigafactories for electrolyzer manufacturing are being commissioned…

Genvia has launched its automated pilot line for high-temperature electrolyzers, designed to produce low-carbon hydrogen. The first demonstrator produced by the manufacturer was tested at Genvia's two factories, in Béziers and Grenoble. In 2025, the demonstrator will be tested under real conditions on the ArcelorMittal site in Lozère.

1 GW

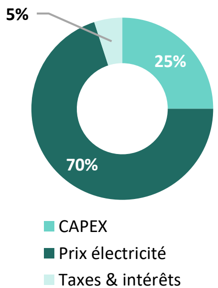
Electrolyzer production in 2025

Should the sector manage to operationalize all electrolyzer production gigafactory projects, while project developers continue to install new capacities at their current pace, then the **6.5 GW target could be achieved**.

The sector must lower its production costs to become more competitive with gray hydrogen

The cost of producing low-carbon hydrogen is 95% dependent on investment costs (electrolyzers) and the price of electricity

The cost structure of renewable H_2



Breakdown of the cost of producing renewable H_2 *

Production (in tons per year)	Capacity (in MW)	Price of electricity (€ per MWh)	Production cost (in € per kg)
150 t	2 MW	€75	€7.40
		€85	€7.80
1,400 t	20 MW	€75	€6.00
		€85	€6.40

At over €7 per kg, the production cost of low-carbon hydrogen is 3 to 4 times higher than that of gray hydrogen. Strengthening the sector's competitiveness involves:

- Scaling up electrolyzer manufacturing through electrolyzer gigafactories to unlock economies of scale.
- Securing a competitive price for low-carbon electricity. This could involve signing long-term (15–20 years) renewable energy supply contracts (PPAs).
- Favorable financing conditions: Between 2021 and 2023, the weighted average cost of capital for hydrogen projects increased from 6.4% to 24%.

McPhy is set to launch one of the first electrolyzer gigafactories in France

In the first half of 2024, McPhy will initiate production at its high-capacity electrolyzer gigafactory in Belfort. McPhy chose Belfort due to the presence of an ecosystem of suppliers.

1 GW
Annual production capacity of electrolyzers in 2026

540
Jobs generated by the project

Industrial companies use PPAs to lock in their electricity prices

In 2023, Lhyfe concluded a **PPA** with VSB Energies Nouvelles to purchase all the power generated by a 13 MW wind farm over a duration of 16 years. This electricity supplies the 5 MW **Lhyfe Bretagne** project, which will be commissioned in December 2023 and is set to produce 2 t of green hydrogen per day.

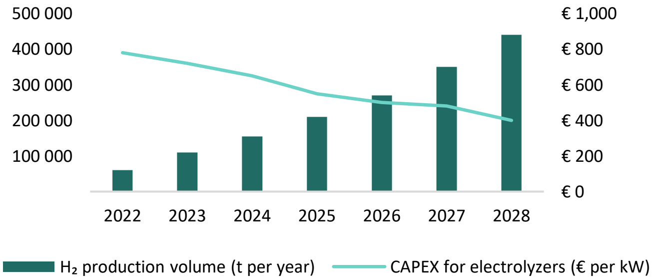
Figures derived from simulations and based on the following assumptions: alkaline electrolyzer technology; 4,000 hours of annual use; the price of renewable electricity is contracted via a PPA; service life of 15 years.

Sources: Capgemini analysis "Reducing low-carbon hydrogen investment and operating costs"; Encyclopédie de l'Énergie; McPhy; Lhyfe

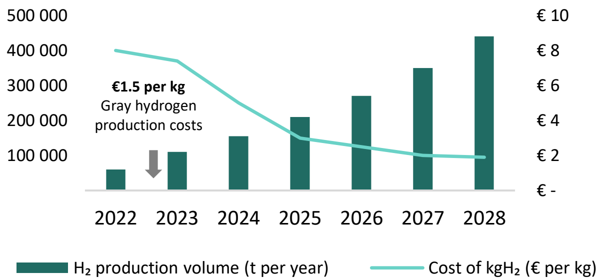
Scaling up production should help lower production costs in the coming years

The average cost of producing low-carbon hydrogen is expected to be halved by 2028, bringing it closer to the production costs of gray hydrogen.

Scaling up of electrolyzer production capacities should halve the CAPEX of electrolyzers by 2028



By 2028, the unit cost of low-carbon hydrogen H_2 is expected to reach €2 per kg, thus approaching the production cost of conventional (gray) hydrogen.



- The average production cost of low-carbon hydrogen is currently around €7.4 per kg. This production cost remains heterogeneous across installations, with some projects incurring higher costs of up to €10–20 per kg. This price variability is due to several factors: the cost of sourcing renewable electricity, hydrogen supply contracts that don't fully cover production capacity, and the low operating time and utilization rate of the electrolyzers (up to 4,000 hours per year only, which corresponds to a utilization rate of under 50%).
- The transition from R&D to industrial-scale production of equipment (primarily electrolyzers), sustained public support (for both production and consumption), the achievement of development objectives in the renewable energy sectors, and securing a competitive and stable long-term electricity price are all crucial factors in enhancing the competitiveness of renewable hydrogen.

Source: Carbon-fee hydrogen roll-out plan

Transport infrastructure needs to be developed to broaden markets for the produced hydrogen while reducing costs.

France must develop a transport network to interconnect various production clusters and link them with cross-border networks to facilitate hydrogen imports.

The use of pipelines and maritime transport is largely overlooked, as road transport is the preferred option

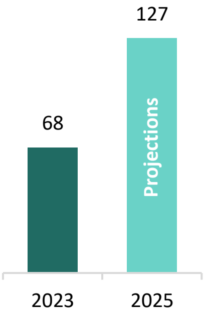
- The choice of transport mode depends on both the volume of hydrogen to be shipped and the distance to be covered. Below 10 tons per day, truck transport is preferred. **Over 10 tons per day,** pipeline transport is more competitive. For distances of a **few thousand kilometers** and upwards, maritime transport may be the most suitable option, depending on specific constraints.
- Low-carbon hydrogen projects in France are primarily localized and focused on **on-site consumption.** The challenge is to connect production and consumption clusters with a dispersed network for mobility applications.
- The **HySow project**, led by **Teréga**, is a hydrogen pipeline network spanning 600 km that will connect the industrial and mobility hubs of Occitanie and Nouvelle-Aquitaine to hydrogen flows produced locally from Southern Europe, the Mediterranean, and the Atlantic Coast by 2030.

16 TWh

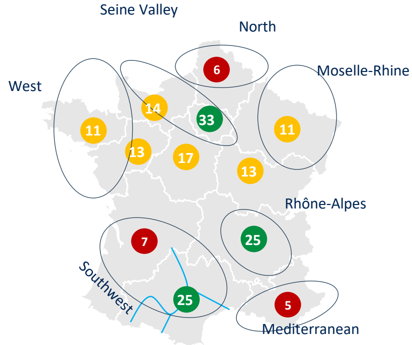
Transportation of low-carbon hydrogen per day

By 2030, the number of distribution facilities is expected to double with the commissioning of major projects.

Number of refueling stations available



Refueling stations in France in 2030



- 7 major consumption clusters should account for 85% of hydrogen demand by 2030. The ambition is to connect these clusters on a national and European scale.
- In 2030, the network of hydrogen distribution facilities should be dense but unevenly distributed across the country. The development priority is placed on three clusters: the Southwest, the Rhône-Alpes region and the Seine Valley, which should account for 53% of the distribution facilities in 2030.

Several solutions need to be implemented to accelerate the growth of the green hydrogen sector

Developing mid-size production projects

- Value chain participants need to develop maturity and experience by executing medium-sized projects on a local scale.
- Large projects are key to accelerating the pace of production and reaching 6.5 GW of capacity.

Increasing the production of renewable electricity at a competitive price

The quality of hydrogen production through electrolysis depends on access to adequate quantities of electricity from renewable sources. In addition, the solar and wind sectors must accelerate their development and achieve maturity.

Ensuring reliability and scaling up the procurement of components

The components used for electrolyzer manufacturing must be reliable and capable of supporting a sufficient electrical load over an extended period (> 4,000 hours). R&D efforts must be maintained to optimize performance and reliability.

Making hydrogen jobs more attractive and accelerating training

The sector must expand training programs tenfold both within companies, to enhance workforce skills, and externally, to attract young talent recently graduated from higher education.

Supporting simultaneous production and consumption

To date, public support has been directed almost exclusively towards the production of hydrogen, but funding must also support consumption/use to avoid imbalances between supply and demand.

Streamlining procedures and facilitating access to financing

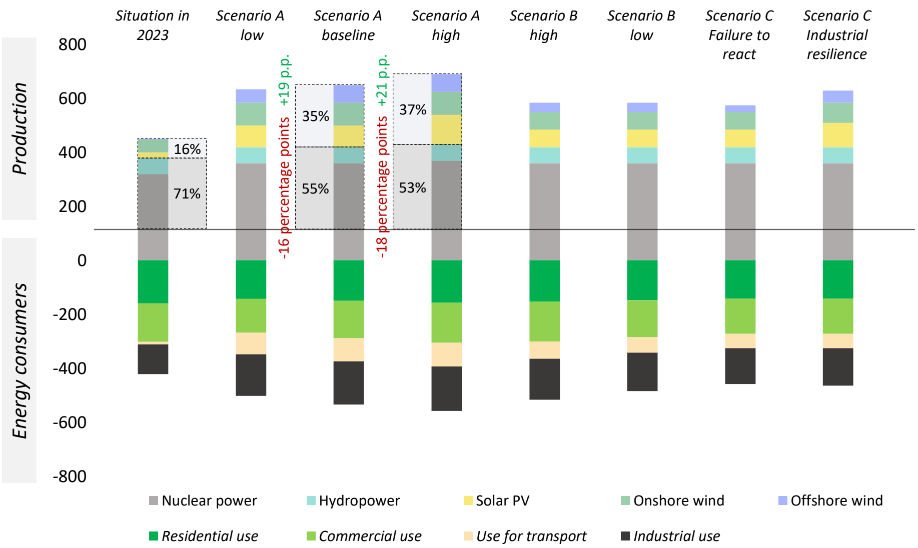
- Administrative procedures must be streamlined, and access to funding must be expedited to **facilitate project execution**.
- Extending this funding to mid-sized projects, rather than limiting it to only “megaprojects.”

3

The key challenges for a controllable system

In response to increasing demand, production growth will be driven by solar PV and wind power

Projection of electricity production and final consumption (TWh) according to RTE's electricity mix scenarios through 2035*



Scenario A – Successful acceleration: rapid growth in electricity production from renewable sources based on a consumption/production mix
Scenario B – Partial achievement: variable levels of delays in electrification, energy efficiency, and energy conservation, along with limited development of renewable energies.
Scenario C – Constrained globalization: macroeconomic and geopolitical tensions persist over an extended period, hindering the development of renewable energies

Source: RTE's 2023 electricity report

All scenarios project an acceleration in renewable energy production

Electricity consumption will rise due to the electrification of end uses, with an increase ranging from +40 TWh to +140 TWh per year by 2035.

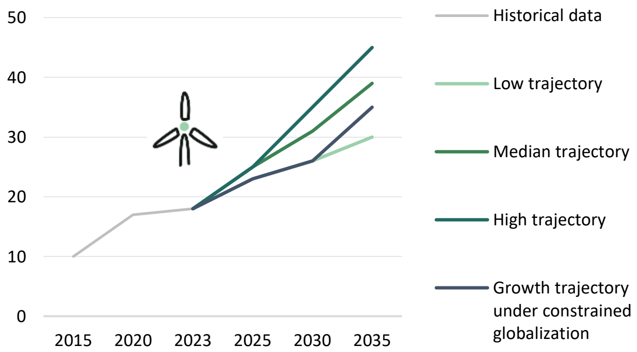
All scenarios indicate stable hydroelectric production and a modest increase in nuclear output (+40–50 TWh) between 2023 and 2035, largely due to the extended development time of new reactors, with no additional reactors expected to come online before 2035.

Renewable energies, both solar and wind, are the only technologies capable of meeting rising consumption demands. Solar and wind production are expected to increase from 90 TWh to 190 TWh between 2023 and 2035:

- Solar: +40–90 TWh per year
- Onshore wind: +20–40 TWh per year
- Offshore wind: +25–60 TWh per year

Installed onshore wind capacity growth is expected to accelerate and reach 45 GW by 2035

Selected development trajectories for onshore wind (in GW)



Installed wind power capacity in 2035 is set not be significantly lower than that initially planned

- If efforts are made to secure the technology and ensure autonomy in terms of components, the rate of installations could align with the baseline scenario starting in 2030 **(1.5–2 GW per year).**
- If the sector experiences disruptions, such as supply chain blockages, this could slow down the rate of installed capacity to around **0.7 GW per year**.

Key success factors for the industry's growth

Bolstering the socio-economic desirability of projects

Wind power projects frequently raise questions. To improve buy-in, it would be best to strengthen citizen consultation, enhance the sharing of value generated by the projects, and free up new land to facilitate the harmonious development of wind farms across the country. Administrative processes for managing appeals must also be expedited to limit delays in the sector's development.

Achieving repowering

French wind farms are entering a repowering phase: the farms built in the late 1990s to early 2000s are reaching the end of their service life. Successful repowering is crucial to increase the output of existing wind farms through the installation of a new generation wind turbines that are both more powerful and more efficient.

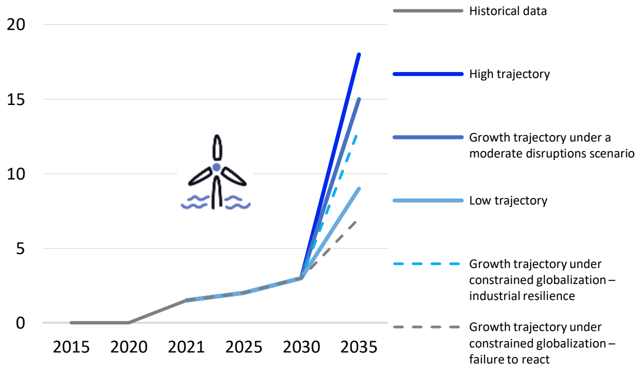
Attracting investment in the industrial production system

Encouraging investment in wind technologies that align with European standards is crucial to producing more powerful and efficient wind turbines. These investments will enable the industrial production system to serve both the domestic and European markets, meeting the increasing demand and supporting the growth of new projects.

Source: RTE's 2023 electricity report

Installed offshore wind capacity growth is expected to continue and reach 18 GW by 2035

Trajectories selected for the development of the offshore wind sector (in GW)



Uncertainties persist over the development of the sector

The pivotal phase of the sector is expected to occur after 2030, presenting several plausible scenarios:

- Acceleration of tender commissioning and rapid growth of floating technology to reach 18 GW in 2035
- An installed capacity of 10–15 GW characterized by delays in awarding tenders and a less pronounced deployment of floating wind power.

Key success factors for the industry's growth

Gaining clarity in planning

Public authorities must establish clear planning and provide increased visibility on future calls for tenders. By offering manufacturers greater visibility, they will be better equipped to anticipate their investments and allocate resources effectively, which is essential for fostering development and innovation in the sector.

Developing skills and attracting future talent

The availability of specialized and expert know-how is crucial in an emerging sector poised for significant acceleration in the next decade. The development of industrial clusters and specialized training centers will allow the sector to sustain its growth rate while ensuring the quality of projects.

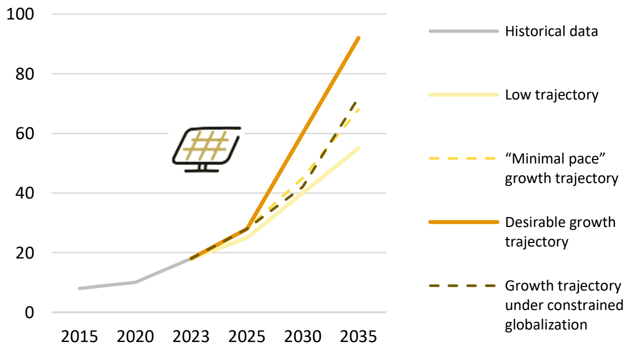
Accelerating the industrial pace

The rapid development of offshore wind power in France and Europe must be matched by an increase in industrial production and the availability of components necessary for the manufacture, assembly, and installation of wind turbines, as well as for the production and installation of cables and electrical substations.

Source: RTE's 2023 electricity report

Installed solar PV capacity growth is expected to accelerate and reach 90 GW by 2035

Development trajectories of the solar PV sector (in GW)



Solar PV growth will continue accelerating

Three favorable trajectories emerge, all indicating acceleration, but to varying degrees:

- A “very low” trajectory, maintaining the pace of the last two years (around +3 GW per year)
- A trajectory with a “minimal” growth rate (of around +4 GW/year), which appears achievable in the short term
- A desirable trajectory, involving a more marked acceleration (approx. +7 GW per year)

Key success factors for the industry’s growth

Accelerating the ability to connect

The project pipeline (amounting to 21.5 GW in late 2023) is equivalent to the currently installed capacity (18 GW). Proper planning and implementation of the SDDR are crucial for enabling industry players to accelerate the pace of connections and ensure the growth of the sector.

Harnessing the potential of agrivoltaics

Agricultural land represents a vast supply of land, covering 26 million hectares in France. In order to achieve an installed capacity of 90 GW, 150,000 ha of agrivoltaic installations are required. This would amount to 10 times more energy production than biofuels. Industry players and public authorities must develop innovative economic models to exploit this resource profitably and competitively while ensuring that the generated value is shared with farmers in accordance with the APER law.

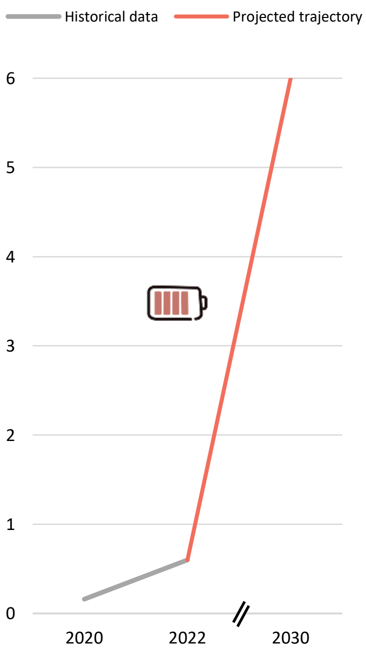
Control over the supply chain

The sector’s strong dependence on imports from China will condition its development and introduces risks of shortages and rising equipment prices. Relocating the solar value chain through gigafactories of modules, panels, etc. will bolster the energy independence of France and Europe while creating jobs in the regions.

Sources: RTE’s 2023 electricity report; APER Law; IFP Énergies Nouvelles

Stationary battery storage capacity growth is expected to accelerate and reach 6 GW by 2030

Projected trajectory for the development of the stationary battery storage sector (in GW)



Key success factors for the industry's growth

Gain visibility into the planning of flexibility needs

It is necessary to assess the capacity requirements for stationary battery storage in the system and establish clear targets. To achieve this, it is necessary to plan the trajectories of flexibility needs, especially in light of new EU regulation requiring member states to assess their flexibility needs for the next 5 to 10 years.

Diversifying revenue streams and making business models more robust

Operators are mainly positioned on frequency regulation and peak demand management services, offering low visibility on revenues. Diversifying revenue streams, for instance through participation in long-term capacity markets with multi-year contracts, will enable developers to ensure project profitability.

Securing industrial investments and developing a storage battery industry

French industry must position itself to seize the opportunities presented by the sector and establish an industrial production system that can serve both the French and European markets. To achieve this, synergies with the electric battery industry for mobility must be leveraged, particularly by expanding the electric battery hub to include batteries for stationary applications.

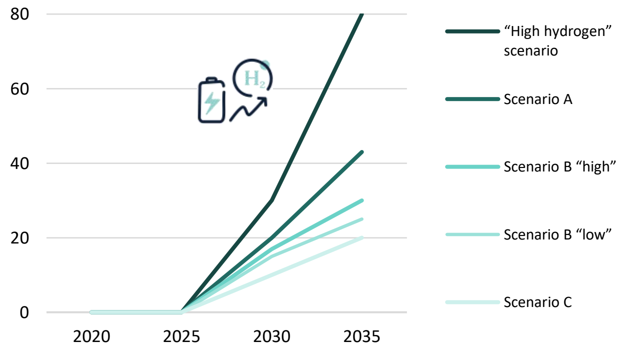
Accelerating technological innovation and developing the next generations of batteries

Continuing to enhance the energy density, lifespan, and safety of batteries is crucial. Research into new battery chemistries, such as solid-state or flow batteries, holds particular promise for reducing reliance on critical materials and lowering manufacturing costs.

Sources: RTE's 2023 electricity report; SDDR; Data Consilium Europa

Low-carbon hydrogen production capacity is expected to increase sharply and reach 80 TWh in 2035

Trajectories selected for the development of the hydrogen sector by electrolysis (in GW)



Low-carbon hydrogen production will serve two main purposes

- Decarbonization of industrial processes, particularly within industrial hubs (steel industry, chemical industry, etc.)
- Decarbonizing heavy mobility, through the direct use of hydrogen in fuel cells for road transport and the production of synthetic fuels for maritime and air transport (SMF and SAF)

Public authorities must implement incentives to stimulate demand, which is a prerequisite for driving growth in production capacity.

Key success factors for the industry's growth

Maximizing the supply of renewable electricity, making production more flexible, and developing storage

The price of electricity represents 60–70% of the cost of producing green hydrogen. The challenge now is to secure a stable and low-cost supply of renewable electricity to reduce costs. The installation of flexible electrolyzers, coupled with hydrogen storage solutions to meet demand during periods of lower production, is key to ensuring rapid development of the sector.

Developing an efficient distribution network

To support new uses, especially in decarbonizing mobility, it is essential to build interconnected transport and distribution networks via pipelines on both a national and European scale. This will help reduce costs and enhance the environmental footprint of distribution. Synergies with existing gas networks must be leveraged to accelerate the emergence of low-carbon hydrogen.

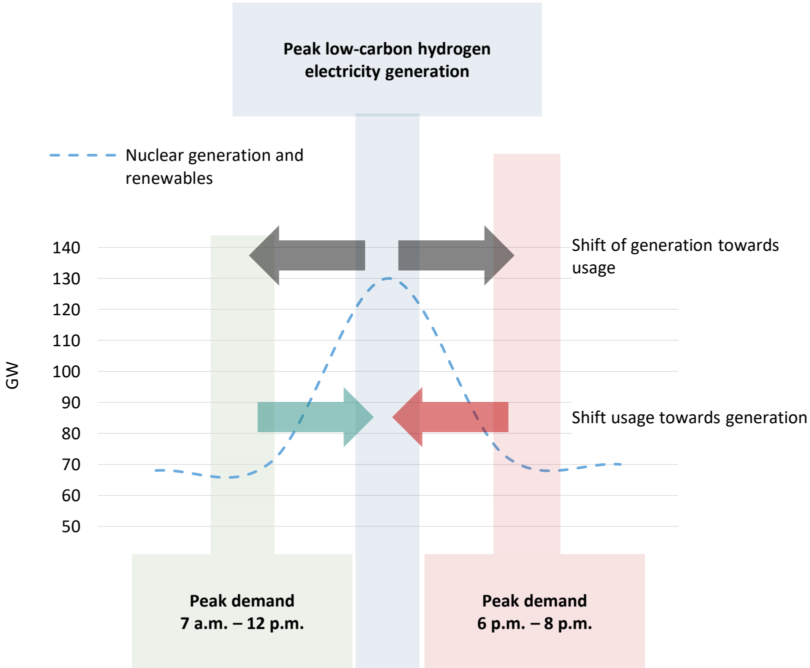
Successfully scaling up the industrial production system

The industry must absolutely succeed in commissioning, scaling up and ensuring reliability (costs, quality, timelines) of component production gigafactories to support production projects with unit capacities that will gradually reach several hundred gigawatts. This will enable economies of scale to be achieved in the production of electrolyzers, which will, in turn, reduce the costs of producing green hydrogen.

Source: RTE's 2023 electricity report

The electrification of end uses and the growing integration of renewable energies are driving an increase in the flexibility of the electrical system.

These flexibilities are required to help balance low-carbon hydrogen power generation and consumption



Source: RTE

A lack of flexibility results in financial losses and undermines the stability of the electricity system.

Without flexibility, the growing integration of renewable energies, particularly solar power, will exacerbate the mismatch between production peaks, which occur around 1 p.m., and consumption peaks, which take place from 7 a.m. to 12 p.m., and 6 p.m. to 8 p.m. This situation will lead to more frequent periods of negative power prices, which will ultimately affect the profitability of production facilities for operators and could place an additional strain on the state budget, as it compensates for some of these losses through “additional remuneration” contracts.

Flexibility helps maximize renewable production and improve system controllability

The development of demand- and supply-side flexibilities should help align consumption and production peaks. This allows for the maximization of renewable production integration into the electricity mix while reducing reliance on fossil thermal power stations for peak consumption management. This will greatly contribute to accelerating the decarbonization of the electricity mix.

Renewable technologies are key to developing flexibilities in the electricity system

Supply-side flexibility	Electricity storage	Demand-side flexibility

Renewable technology involved

Solar PV/wind

Renewable installations can be quickly started or stopped and adjust their production based on weather conditions, thus natively providing downward flexibility.

Additional flexibilities can be developed through the construction of hybrid power plants (integrating storage capacities directly within renewable installations). By storing renewable electricity during periods of surplus and injecting additional volumes during periods of shortage, these power plants allow developers to maximize the value of their production.

Battery (stationary use)

Stationary battery storage can help manage peak electricity demand. By storing electricity during low-demand periods and releasing it during peak consumption, they help reduce the reliance on quick-start fossil fuel power stations, which are typically more expensive and more polluting.

Green hydrogen

The electrolysis process (when resorting to flexible electrolyzer technologies, which are the only ones capable of withstanding load variations) can be adjusted based on electricity availability, enabling variable consumption and thus contributing to grid stabilization.

When surplus renewable electricity is available, electrolyzers can increase their output to take in this surplus, converting it into green hydrogen for storage.

Conversely, during periods of renewable electricity shortages, stored green hydrogen can be converted back into electricity thanks to fuel cells in order to meet demand.

Source: Capgemini Invent analysis

Renewable technologies are becoming essential in meeting the needs of the needs of the electricity system

01 Anticipating and highlighting production forecasts

Renewable energy producers, like other power producers, must submit production forecasts while considering all factors that impact the energy fed into the grid, such as maintenance, voluntary or regulatory restrictions, and shutdowns requested by the aggregator, especially in cases of negative spot prices.

The programming system is crucial for RTE. Accurate forecasts are the first step in enabling RTE to fulfill its missions as a **transmission system operator, by providing it with the best assumptions to anticipate operational situations and make proactive decisions in restoring the supply-demand balance, managing network congestion, and ensuring voltage regulation**.

02 Participating in balancing mechanisms

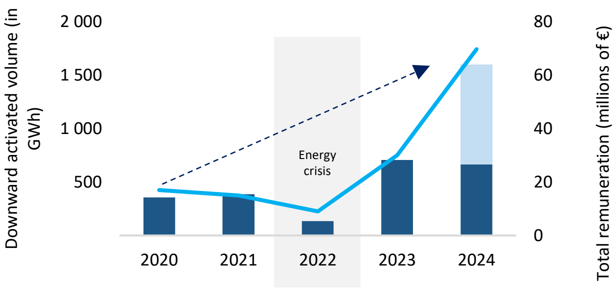
To balance supply and demand, renewable energies can and must adjust their output.

Indeed, they **exhibit strong agility in responding to economic signals from wholesale markets through aggregators and take part in RTE's balancing mechanisms** via manually activated reserves such as the adjustment mechanism (mFRR), and ultimately engaging in the European MARI platform (mFRR), as well as its automatic reserves platforms (aFRR and FCR).

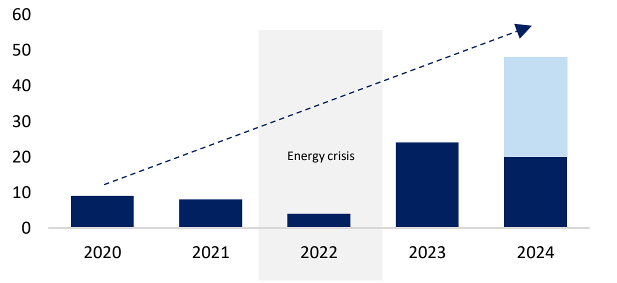
The participation of renewable energies in these mechanisms is set to be strengthened.

What are the needs associated with renewable energies and the adjustment mechanism?

Downward activated volumes at negative prices over time



Changes in the number of notifications for insufficient downward offers



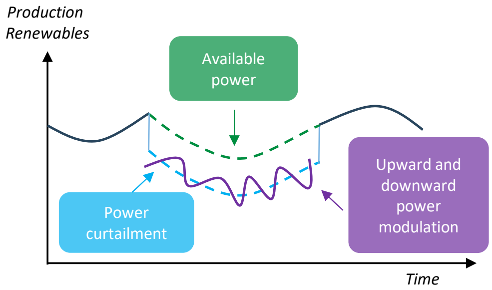
Downward adjustment volumes at negative prices are increasing sharply and RTE is increasingly facing insufficient supply to implement downwards adjustments

- Currently, renewable energies play a very marginal role in the adjustment mechanism, which is still primarily based on historical means of production connected to the public transmission network (nuclear, thermal, and hydroelectric power plants). Only a few players offer renewable energy sources like onshore wind farms on the adjustment mechanism, with the number of adjustment entities (supporting offers in the adjustment mechanism) increasing from 1 in 2022 to 5 in 2024, representing a maximum power of less than 400 MW.
- Renewable energies (wind, solar) have a decisive role to play in balancing the grid, for downward adjustments in particular. This presents opportunities for renewable energy sources to offer downward bids allowing them to enter the “merit order” system, even at negative prices. To participate, operators must join with an aggregator or become a balancing responsible party.

* 665 GWh and €29 million in remuneration between January and May 2024, extrapolated to 1,600 GWh and €70 million for the year 2024
** 20 downward notifications between January and May 2024, extrapolated to 48 for the year 2024

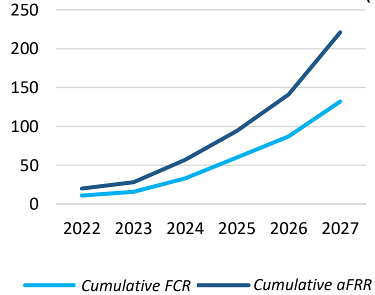
The capacity of electricity generating facilities to modulate their power must develop to meet the increasing demands for primary and secondary reserves.

Illustration of power modulation



To participate in frequency control services, a renewable electricity generating facility must curtail its output to modulate according to the frequency and/or level signals provided by RTE. This amounts to operating the generating facility slightly below its maximum capacity to free up flexibility by modulating production either upwards or downwards.

Obligations in terms of capacity for frequency control services in renewable power generating facilities connected to the public transmission network (in MW)



The growth of renewable energies connected to the RPT will increase the participation of renewable energies in the frequency control services (FCR primary reserve and aFRR secondary reserve).

Renewable energies will have to take part in frequency regulation system services

- Reserve requirements will rise to facilitate the operation of an electricity system facing increasing uncertainties. Some renewable electricity generating facilities are required to take part in frequency control services by using part of their power. To achieve this, RTE must verify the suitability of the electricity generating facilities, which involves conducting tests that are subsequently analyzed and validated by RTE.
- However, RTE’s current control tools have not yet been tested on the power variations specific to wind and solar PV, complicating the estimation and validation of the adjustments provided by renewable production facilities, which is nonetheless essential for ensuring their effective participation in frequency control services. As a result, no renewable energy facility is currently contributing any frequency control services, although some operators have responded to RTE’s call to participate in experiments.
- It is crucial to conduct experiments where RTE will provide a frequency and/or level record to test the response of renewable energy facilities using its control tools. The renewable energy facilities required to participate in frequency control services will need to undergo these experiments and/or the certification process. Additionally, non-obligated facilities that are already connected to the grid can also volunteer to participate in these tests, thereby contributing to the overall enhancement of the flexibility and reliability of the electricity system.

Sources: Capgemini Invent analysis; RTE

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Renewables Power Systems Observatory
2024