# Électricité de France: The Contribution of French Nuclear Fleet to the Flexibility of the Electric System

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French electricity generation is characterized by a very high share of zero-carbon production. With 495 TWh generated in 2019 (NREL 2019) out of 538 TWh, nuclear and renewable energies (hydro, wind, solar, bioenergy) represent 92% of the total electricity generated. With a positive balance of 56 TWh in 2019, France is also a major exporter of electricity in Europe. The demonstrated flexibility of French nuclear power plants, which today account for about three-quarters of the zero-carbon production, clearly shows the way for the complementarity of variable renewables and nuclear in a decarbonized economy.

## 1.1 Nuclear Flexibility Already Utilized in France

The nuclear reactors in service in France have a considerable amount of built-in flexibility. French nuclear reactors are designed to be able to reduce output from 100% to 20% of rated capacity twice a day in under 30 minutes, depending on the type of reactor. Thus, they have a ramp up/down ability of 30–40 MW per minute (about 3% of the nominal capacity), which can be compared to normal ramp-up abilities of gas combustion turbines (7–12 MW/min, 5%–8% of the nominal capacity) or combined gas cycles (15–40 MW/min, 3-7% of the nominal capacity) and is adequate to meet the needs. To keep pace with fluctuating demand, a major load variation program is agreed upon in advance with the grid operator.

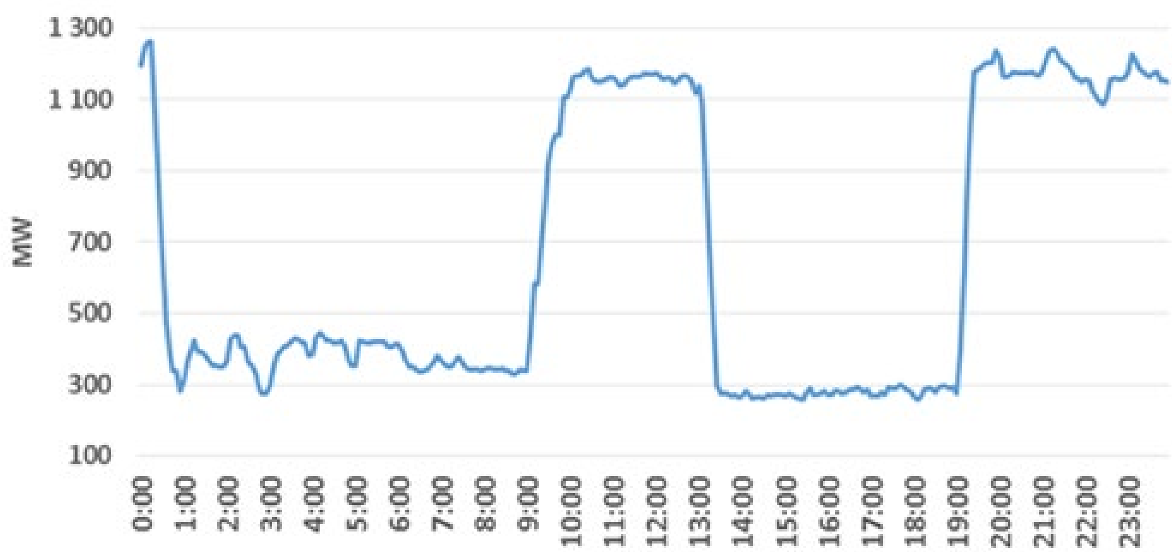


**Figure 1. Example of power variations over 1 day, Golfech 2 nuclear power plant, 1,300 MW**

Source: Jun Zeng, EDF. 

*This document encompasses one section of a larger report, titled Flexible Nuclear Energy for Clean Energy Systems. The full report can be found at https://www.nrel.gov/docs/fy20osti/77088.pdf. The author(s) of each section is/are solely responsible for its content; the publication of these perspectives shall not constitute or be deemed to constitute any representation of the views or policies of any Governments, research institutions, or organizations within or outside the NICE Future initiative.*

Figure 1 shows electric capacity delivered by Reactor 2 at the Golfech nuclear power plant in the southwest of France over 1 day on May 3, 2020. Output was cut sharply twice, in the middle of the night and in the afternoon, with variations from 1,250 MW to 300 MW within half an hour.

This flexibility is amplified by the fleet effect. At the beginning of 2020, France's 58 nuclear reactors had a combined net capacity of 63 GWe operated by EDF. These reactors could, on average, ramp up to 21 GWe within 30 minutes. This is a significant modulation capacity, as nuclear reactors supply an average of about 50 GWe over the year. The nuclear fleet also contributes to power system stability as nuclear reactors can make minor automatic load variations to control grid frequency.

The nuclear fleet also provides seasonal fluctuations. Since nuclear fuel can be considered a finite life stock, both short-term nuclear flexibility and medium-term fuel management can be jointly optimized so that nuclear power plants are available when needed. The number of refueling outages scheduled simultaneously thus fluctuates greatly over the year, with more than 15 reactors out of 58 shut down for refueling at the same time during the summer, when demand is lowest.

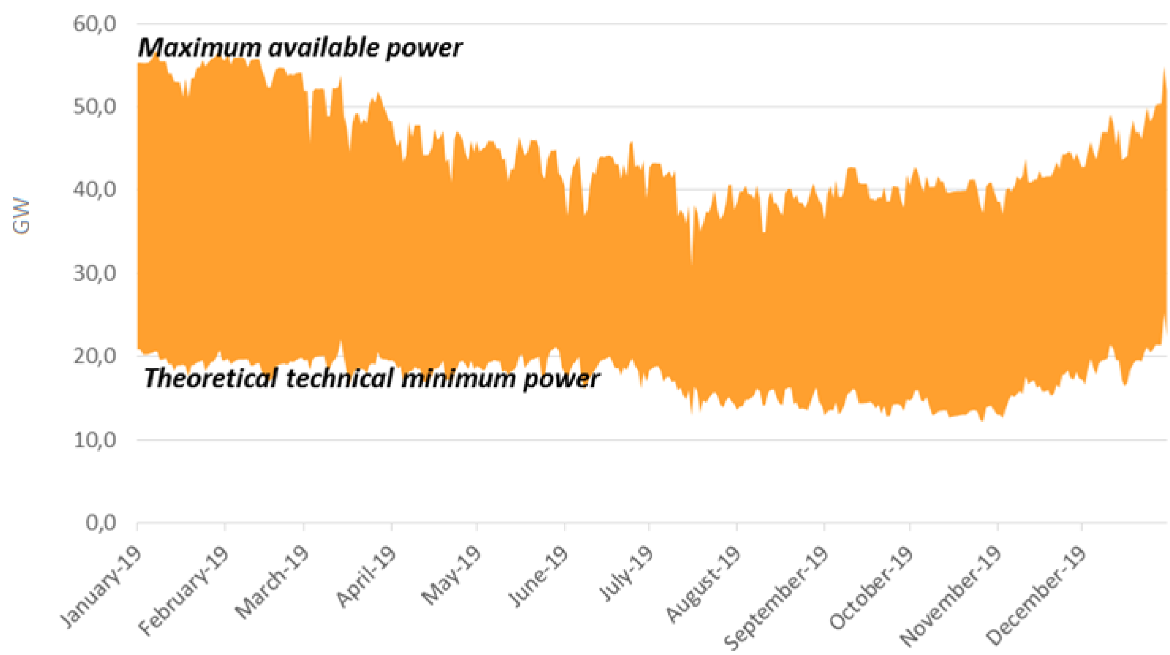


**Figure 2. Maximum available power and technical minimum power of the EDF nuclear fleet in 2019**

Source: Jun Zeng, EDF. 

## 1.2 Today's Flexibility Reflects the Success of the French Nuclear Program

In the space of 25 years, between 1974 and 1999, EDF built and commissioned 58 reactors, which now have an average age of 35 years. Thanks to standardization and series effects, nuclear has been and is still very cost-competitive. The favorable economics of French nuclear reactors meant that it was cost-effective to run the plants beyond base load generation to provide load-following power. Nuclear accounts for the largest share of the French power mix, which implies a modulation requirement to keep up with daily fluctuations in demand: a low overnight and a peak at around 7 p.m. in winter and around 1 p.m. in summer, with an average supply of up to 60 GWe in winter and 40 GWe in summer.

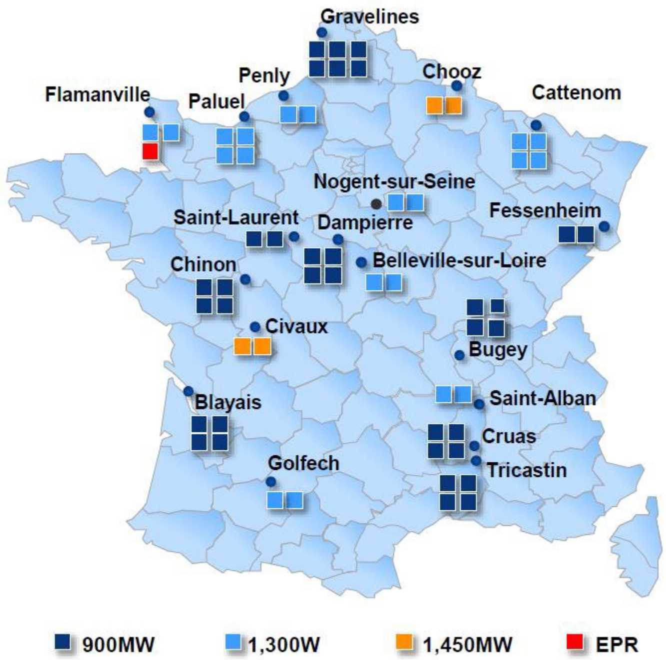


**Figure 3. Nuclear power reactors in France**

All French nuclear reactors are PWRs operated by EDF and were supplied by the same vendor.

Source: EDF. Used with permissions. 

## 1.3 Complementarity of Variable Renewables and Flexible Nuclear Is a Pillar of Decarbonized Power Generation

Electrifying end uses and unleashing energy savings across all sectors are keys to fighting climate change and decarbonizing the energy sector. Because of the resulting surge in demand for zero-carbon electricity, the complementarity of renewables and flexible nuclear is a pillar of the energy transition. Today, it already makes good economic sense, as it leads to competitive prices for consumers: in France, electricity prices for household consumers are 18% lower than the European Union average. Moreover, with $CO_2$ emissions representing 49g/kWh in 2018, less than one-fifth of the European average, France already has low-carbon electricity.

France is fully committed to a zero-carbon energy objective for 2050. According to the French low-carbon strategy, electricity consumption should reach around 600 TWh in 2050, a 30% increase from the current level, mainly due to electrification of end uses. The French transition energy law sets a 50/50 goal in 2035 for nuclear and renewables generation in the electricity mix, which will require far greater flexibility. Given the strong increase in renewable production and the future closure of French nuclear reactors at the end of their lifespan (today scheduled between 50 and 60 years), the successful balance between renewables and nuclear energy implies a need for new reactors being commissioned in the coming decades.

Accommodating a growing share of variable renewable energies (wind, solar PV) will be a challenge for the power system. Rising to that challenge will require not only strengthening the grid but also adding zero-carbon backup to maintain electricity quality and the supply-demand balance. Thus, nuclear will, over the long term, be a proven source of operational flexibility, along with other sources being developed (e.g., batteries, vehicle-to-grid, demand-side management, other dispatchable low-carbon sources). Tapping this potential will require skills and expertise both in design engineering and operations, to guarantee that reactor operations meet all safety standards.

A question often raised relates to the impact of flexibility on operating performance. For instance, whether additional maintenance is required and/or plant availability is affected. Studies conducted by EDF found that the impact exists but is not significant. If the level of flexibility required increases in the coming decades, then market design will have to be adapted to maintain an adequate level of remuneration of flexibility with future market conditions.

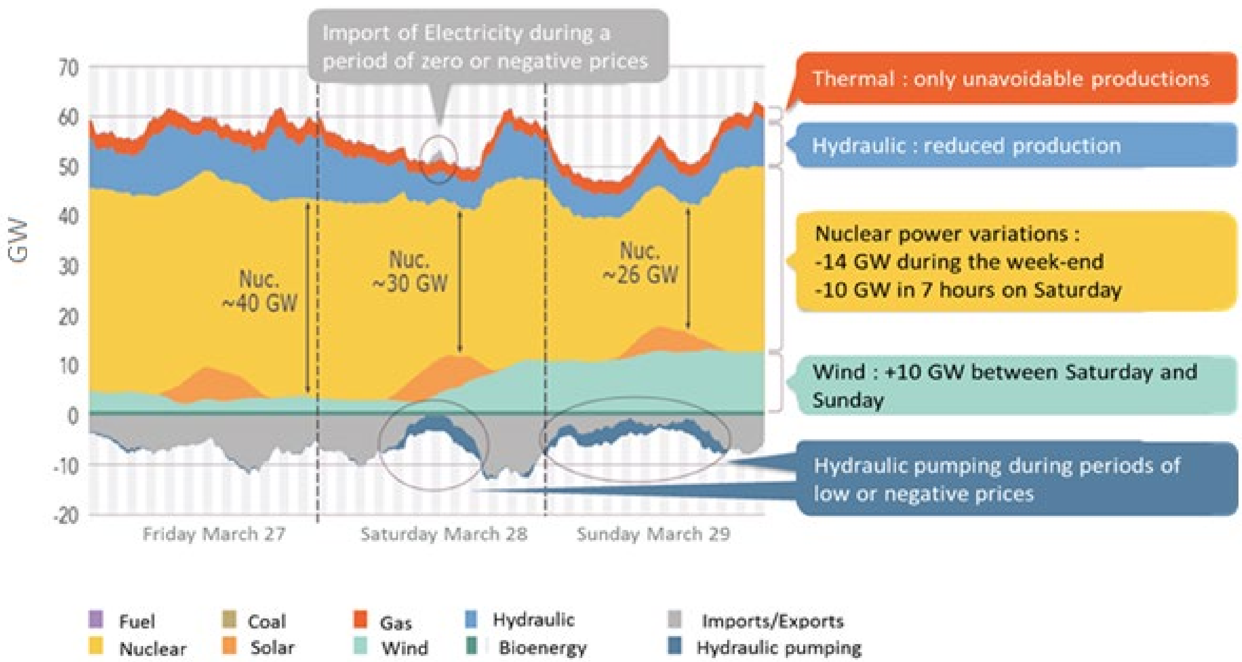


**Figure 4. Different metrics recorded between March 27 and March 29, 2020**



During the 3 days, nuclear power ramps down from 40 GW to 30 GW in a few hours, and then to 26 GW when power demand and exports are low and solar and wind productions are high. Imports and hydraulic pumping take place when prices are low or negative.

## 1.4 Innovations That Have Made Flexible Nuclear Possible in France Can Be Widely Replicated

Innovation has allowed EDF to operate its nuclear plants in a flexible manner and to develop supporting technical skills for nuclear operators. Key areas of innovation are design modifications, extended safety studies, and control room operation, which requires well-trained personnel.

**Enhanced Design:** The design of French nuclear power plants has evolved to include features not found in standard PWRs. These modifications have primarily involved using different types of rods and changing their position in the core depending on power levels. The use of special "gray rods" composed of materials that absorb fewer neutrons than standard control rods makes it possible to modulate chain reactions more precisely.

**Extended safety studies:** Safety studies have been extended to consider a wide power range. Dedicated specifications, validated by the French Nuclear Safety Authority, are applied to flexible operation.

**Well-trained operators:** Control room operators receive specific training in this mode of operation on full-scope simulators that are exact physical replicas of control room equipment. Assistance tools have also been developed over the past 15 years.

What has been accomplished in France can be duplicated elsewhere in the world. Developing new reactors with these operating procedures integrated as early as the design phase will be key to controlling the economic impact of this flexibility. The costs associated with new nuclear will determine where this powerful source of zero-carbon flexibility fits in the merit order relative to other tools that will be available moving forward.

## 1.5 References

NREL. 2019. "2019 Annual Technology Baseline." Golden, CO: National Renewable Energy Laboratory. https://atb.nrel.gov/.