

Nuclear Power Plant flexibility at EDF

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Title: Nuclear Power Plant Flexibility at EDF

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Abstract – *Based upon existing experience feedback of French nuclear power plants operated by EDF (Electricité de France), this paper shows that flexible operation of nuclear reactors is possible and has been applied in France by EDF's 58 reactors for more than 30 years without any noticeable or unmanageable impacts: no effects on safety or on the environment, and no noticeable additional maintenance costs, with an additional unplanned capability load factor estimated at only 0.5%. EDF's nuclear reactors have the capability to vary their output between 20% and 100% within 30 minutes, twice a day, when operating in load-following mode. Flexible operation requires sound plant design (safety margins, auxiliary equipment) and appropriate operator skills, and early modifications were made to the initial Westinghouse design to enable flexible operation (e.g., use of "grey" control rods to vary reactor core thermal power more rapidly than with conventional "black" control rods). The nominal capacities of the present power stations are sufficient, safe and adequate to balance generation against demand and allow renewables to be inserted intermittently, without any additional CO_2 emissions. It is a clear demonstration of full complementarity between nuclear and renewable energies.*

Keywords – *Flexible operation, Nuclear Power Plant, Renewable energies*

I. INTRODUCTION: NUCLEAR AND RENEWABLE ENERGIES ARE THE TWO PILLARS OF FRANCE'S LOW CARBON ELECTRICITY

The fight against climate change has entered a crucial phase with the objective set by COP 21 to keep global warming "well below" +2 °C at the horizon 2100. Today, energy accounts for most CO_2 emissions worldwide and the electricity sector in particular is a prime candidate for deep decarbonization. A recent MIT study[1] says that unless nuclear energy is incorporated into the global mix of low-carbon energy technologies, the challenge of climate change will be much more difficult and costly to meet. Although nuclear energy raises the problem of nuclear waste management, solutions have been identified, and it is the climate change challenge that is overwhelming.

In this respect, France – which already has low carbon intensity facilities – is a step ahead of its major European neighbours. This low carbon and competitive mix must be preserved in the long term, drawing on the complementary relationship between renewable energy sources and nuclear energy. France's electricity generation is built on a mix of varied generation units, based upon nuclear power plants (NPPs), renewable energies sources (RES) consisting of hydropower plants, wind turbines, solar farms or biomass plants and a few remaining set of conventional units.

With an overall net generation capacity of 129.3GWe (92.3GWe in mainland France), generating 580.8TWh (424.7TWh in mainland France) in 2017[2], the EDF group is one of the world's leading electricity producers. EDF's fleet generates 87% carbon-free electricity, due to the predominance of nuclear and hydropower generation facilities, in an increasingly restrictive environmental regulatory context.

EDF is among the world's 10 largest global power suppliers, and produces the smallest amount of CO_2 per kilowatt-hour, with direct emissions currently at $82gCO_2/kWh$[2] ($25gCO_2/kWh$ for EDF France Mainland), which is far less than the world average for the sector ($506gCO_2/kWh$ in 2015) and the average for the main European electricity providers ($275gCO_2/kWh$ in 2016). EDF group's decarbonization strategy is first and foremost based on an ambitious industrial policy focused on a low-carbon generation with a balanced mix of nuclear and renewable energy.

More specifically concerning nuclear power, EDF is the world's biggest NPP operator. EDF operates 58 nuclear units in mainland France, based on PWR (Pressurized Water Reactor) technology; A "unit" is defined here as a generation facility including a reactor, steam generators, a turbine, a generator, the related equipment and the buildings that house them. These units are spread over 19 sites, with an average age of 32 years. They are divided into three series according to the electrical power available: a 900 MW series consisting of 34 units, a 1,300 MW series consisting of 20 units, and a 1,500 MW series consisting of 4 units.

Built in the 1980-90s and originally based on a Westinghouse design, with upgrades implemented by EDF and Framatome, the French nuclear fleet grew at a quick pace, reaching about 72% of the total electricity generated in France[3] in 2017 (see fig.1), 89% of electricity generated by EDF alone in mainland France[2] (see fig.2). Thus, EDF's nuclear facilities are already giving France a major lead compared to its neighbours in terms of curbing greenhouse gas emissions, while still ensuring lower electricity costs.

In the past 30 years, EDF has striven to further increase the operational flexibility of its reactors, to make them more compatible with load fluctuations and to the intermittent renewable energy sources that are a crucial and growing part of any energy mix. France's situation is particular in that nuclear units must themselves be able to provide this flexibility of generation, because of their predominant share of electricity supply. EDF relies on feedback from 30 years' experience, showing that, except for some minor impacts on the secondary system (water/steam cycle), flexibility has no significant operational impact: in particular, nuclear safety is not affected.

In the rest of the world, most of nuclear plants run on a full-power basis, also known as base-load operation, since they contribute to a minor share of electricity supply (typically 10 % to 30%): flexibility is achieved by gas, coal and other fossil fuel units, contributing to additional CO_2 emissions.

To ensure a continuous supply of electricity, it is therefore necessary either to store a part of the electricity generated by renewables and use it when wind and sun are not available, or to introduce generation units able to easily modulate their own electricity output.

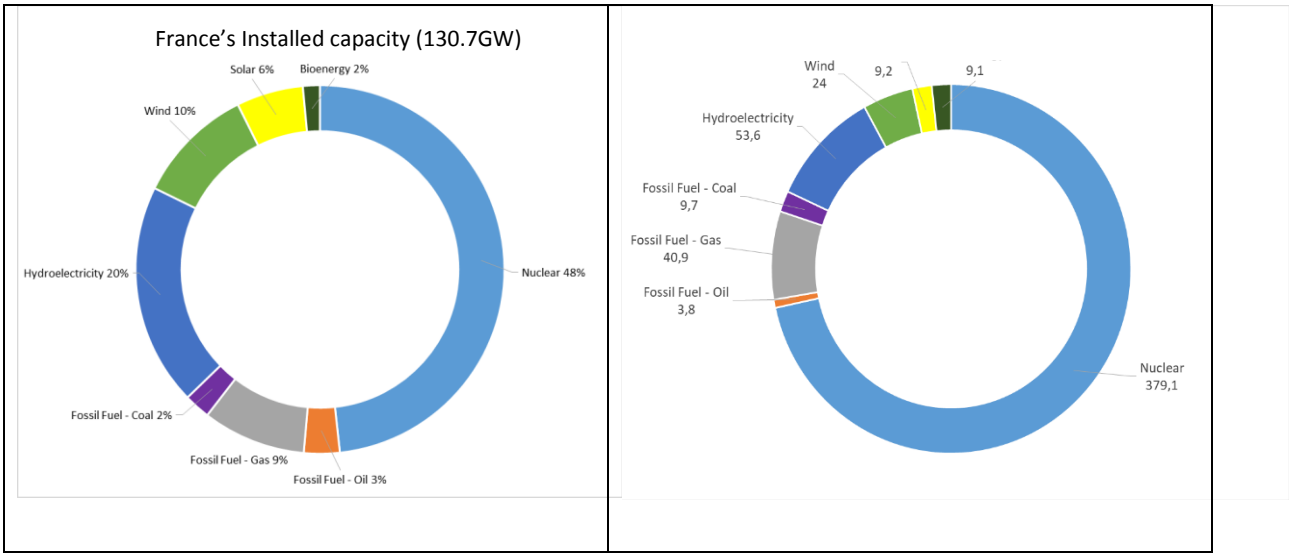


Figure 1. France's 2017 installed capacity and electricity output[3]

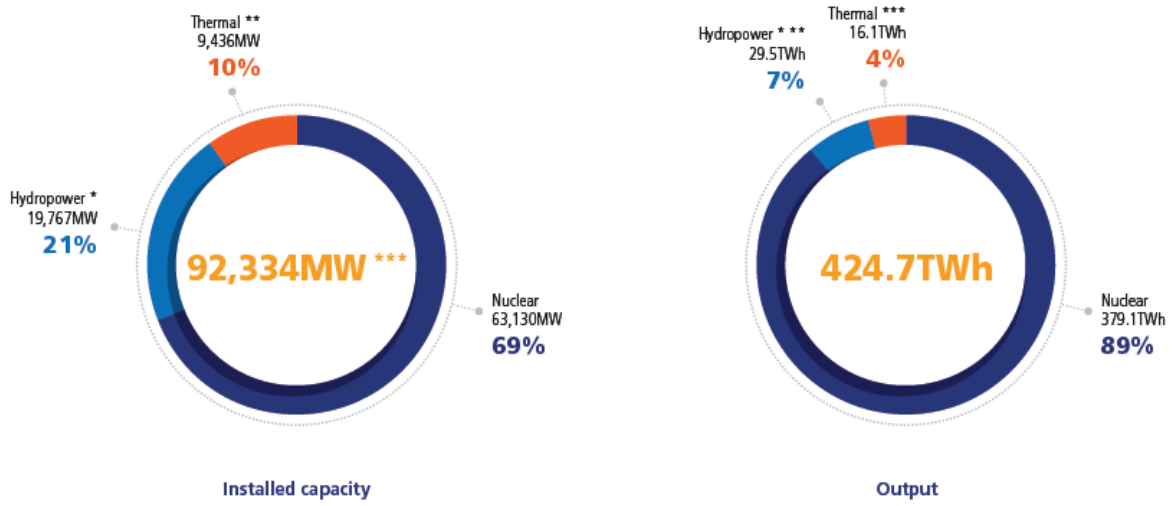


Figure 2. EDF's 2017 installed capacity and electricity output in mainland France[2]

II. WHAT IS PLANT FLEXIBILITY?

Although high electricity storage capacity is the current target for electricity utilities worldwide, electricity cannot yet be stored on a significant industrial scale[4]. Thus an electrical power system must be able to adjust to rapidly varying electricity demand/generation balance. Whereas balancing levers exist on the demand side, this document focuses on balance on the generation side.

Base-load operation refers to a steady power output which depends on the unit series[5]. Power changes may occur, whether planned (reduction or shutdown for refueling or periodic maintenance) or unplanned (specific maintenance to address emergent plant issues); but for a base-load operated plant, these are triggered by events occurring at plant level rather than grid system level. Historically, most of the nuclear power plants in the world have been operated as base-loaded units: operating at a constant power level is simpler and less demanding in terms of plant equipment and fuel, not to mention the economic benefit to operate as long as possible nuclear power plants that have high investment costs with low variable costs. (nuclear variable costs are mainly fuel-related costs and represent less than 30% of operating costs).

In contrast to base-load operation, flexible NPP operation refers to any mode of operation in which power output varies to meet the demand of the electrical grid system. As electricity demand varies continuously, the gap between output and demand results in variation in grid frequency: frequency drops when demand increases (lack of generation) and rises when demand decreases (excess of generation).

Two types of flexibility are usually distinguished: large load variation programs agreed in advance between grid operator and plant operator, known as "load following" (applied to nuclear plants in France but not in all countries), and minor automatic load variations aimed at controlling grid frequency, known as "primary and secondary frequency control", usually implemented on all nuclear plants when available. These two types of flexibility can be superimposed.

In Load Following mode[6], the nuclear power plant follows a load pattern determined to match the electrical demand expected by the grid operator (depending on time, day, week, season or emergent grid events) and the actual capabilities of the plant. The power output is set manually by the plant operator. Power ranges between maximum output (depending on the series: i.e., 900 MW, 1,300 MW or 1,500 MW) and a minimum output corresponding to the minimum required to supply the automatic plant controls (about 20% of the nominal power of the plant: i.e., 180 MW for standard 900 MW plants, 260 MW for 1,300 MW PWRs, and 370 MW for 1,500 MW PWRs). In France, a nuclear power plant is able to ramp up or down between 100% and 20% of nominal power in half an hour, and again after at least two hours, twice a day.

In Frequency Control mode, the power plant has to monitor the frequency of the grid and immediately adapt its level of generation in order to keep the frequency stable at the desired value (50 Hz ± 0.5 Hz in Europe). This is achieved through an Automatic Frequency Control (AFC) process, which acts at different amplitudes and time scales.

Primary frequency control allows short-term adjustments (in less than 30 seconds) and is used to stabilize grid frequency transients. An automatic control implemented on the turbine increases the electrical output if the frequency falls, or decreases output if the frequency rises.

The magnitude of variation under primary frequency control is set at ±2% of the unit's nominal power.

Secondary frequency control operates over a longer timeframe (up to 15 minutes), and is aimed at what is known as the "frequency restoration reserve", an operational reserve activated to restore grid frequency to the nominal frequency at national and European scale. An automatic signal is sent remotely by the grid operator to the plant to change its power output within a range of ±5% of the unit's nominal power (i.e., 50 MW for 900 MW plants, 65 MW for 1,300 MW plants and 75 MW for 1,500 MW plants).

Taken together, primary and secondary control provide additional flexibility up to ±7% of the unit's nominal power (i.e., 70 MW for 900 MW series, 90 MW for 1,300 MW series and 100 MW for 1,500 MW series).

An example of a flexible operation power record for a French NPP is shown in figure 3 below. It illustrates typical power variations in a single reactor (unit) at a 1,300 MW PWR plant over a 24-hour period.

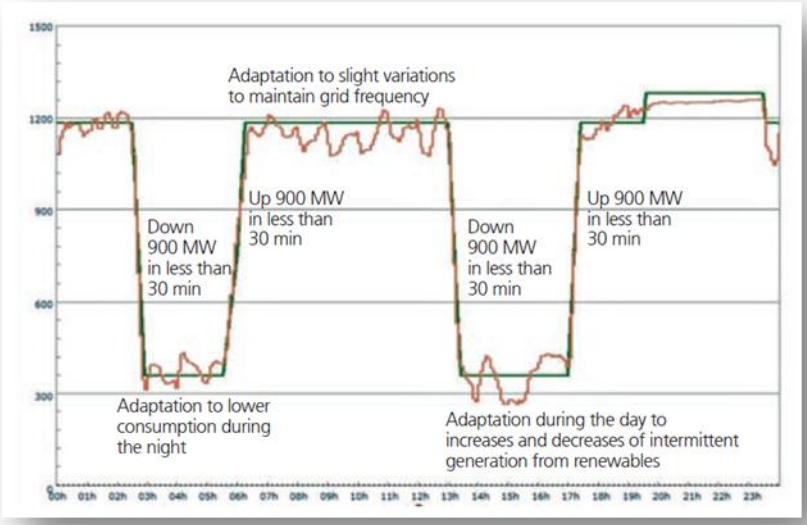


Figure 3. Power generated by one plant reactor (1,300 MW capacity) over a 24-hour period in Sept' 2015, in response to variations in electricity demand and in supply of local intermittent renewables

Load-following and frequency control are two levers of flexibility at the within-day timescale. Other levers are worth mentioning. On a timescale of a week, plant availability can be adjusted by shifting routine tests by a few days. On a seasonal timescale, refueling and maintenance operations can be scheduled during periods of low demand, providing 100 additional TWh during the season of highest demand.

A study by EDF showed that, until 2030, the nominal capacities of EDF's nuclear NPPs (2 variations per day: change from 100% to 20% power in half an hour) are sufficient to balance the intermittency of renewables in most situations[7]. EDF is able to keep two in three units in flexible mode (capable of power variation between 100% and 20% of nominal power). In spring or summer, when 12 to 15 reactors are shut down for maintenance or reloading, about

45 nuclear units out of 58 remain connected to the grid. If 30 units can vary their output by 500 MW each, the total fleet has a flexibility capacity of 15,000 MW, in addition to the existing capacities of hydro-generation, fossil-fuelled power stations and export/import surplus.

EDF has also striven to limit or optimize operating rules which could reduce the present flexibility: a simple example is the optimization, so as to meet flexibility requirements, of scheduling of periodic full-power tests such as flux mapping tests (performed to calibrate core instrumentation).

III. NUCLEAR AND RENEWABLE ALLIANCE: GETTING ALONG WITH FLEXIBILITY

There are two main constraints for dispatchable power plants: power variations due to consumers' fluctuating demand, and the inevitable fluctuations of intermittent renewable energy generation because of varying weather conditions and the day/night cycle. This requires flexibility from large power plants, such as nuclear or fossil-fuelled units, in addition to hydro-generation which is naturally flexible.

III.A. ELECTRICITY CONSUMPTION

Electricity consumption obviously varies constantly. In France, the annual difference between maximum and minimum hourly consumption can exceed 60 GW: 30199 MW on August 13 at 7 am and 94190 MW on January 20 at 9 am. Risk in supply-demand balance differs between winter and summer, as seen in fig.4 and fig.5, mainly due to heating in winter.

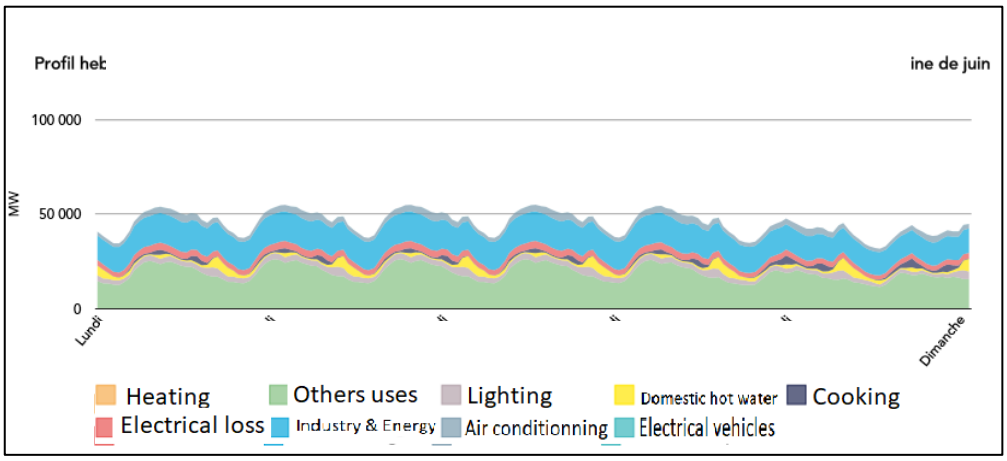


Figure 4: demand in France in a 2017' summer week

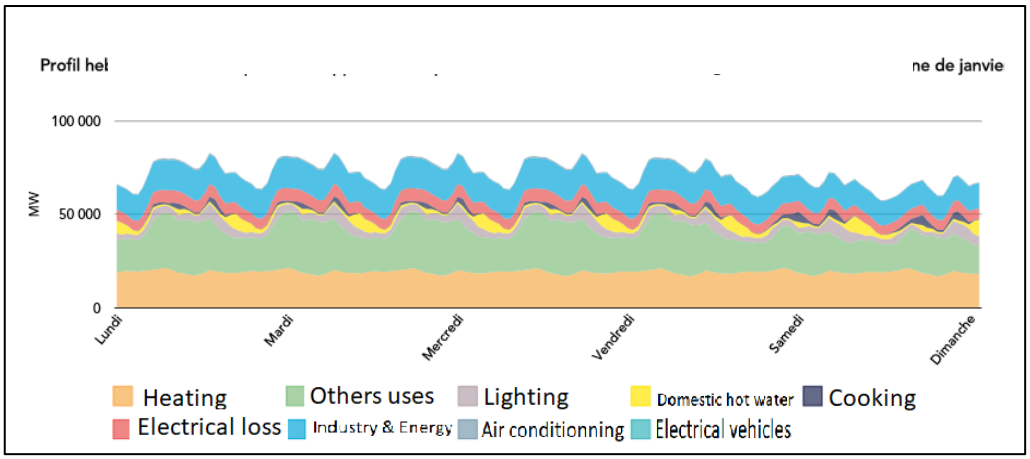


Figure 5: demand in France in a 2017' winter week

In terms of frequency control, the winter risk (lack of capacity) is greatest at the peak hour of 7 pm on weekdays, whereas the summer risk (risk of over-capacity) is mainly around the lowest consumption levels, encountered early morning at weekends, between midnight and 5 am. French generating facilities are sized to meet the winter consumption peak.

III.B. INHERENTLY VARIABLE RENEWABLE ENERGY: WIND AND SOLAR

Renewable energy sources are of two types: dispatchable or controllable sources such as hydroelectricity, biomass and geothermal power; and non-dispatchable sources, also known as variable renewable energies (VRE), that are intrinsically highly fluctuating (like wind and solar power).

Approximately 1,800 MW of renewable energy have been added to the French generation capacity every year since 2010, the equivalent of one new nuclear unit every year. Wind power capacity amounted to 13,559MW as of December 31, 2017[3]. Wind power generation saw a sharp increase of 14.8% compared to 2016. A new maximum wind turbine production rate was recorded at 1.30 pm on December 30, with power output of 11,075 MW. With 887 MW new capacity in mainland France, solar energy capacity reached 7,660 MW in 2017. Solar power generation increased by 9.2% compared to 2016.

The 2015 French "Energy transition for sustainable growth" law set a target of 40% of renewables in power generation by 2030 in France.

In 2017, RTE - the French Transmission System Operator - issued a comprehensive study to identify challenges and solutions for upcoming developments in the electricity production/consumption balance[8]. The document forecast an increase in wind capacity of 1.5 to 2 GW per year and an increase in solar capacity of 1.4 to 1.8 GW per year up to 2023. Beyond 2023, the pace of development is expected to be maintained, reaching 40 to 51 GW wind capacity and 28 to 36 GW solar capacity by 2030, for a production of 96 to 122 TWh for wind energy and of 33 to 43 TWh for solar energy (see fig. 6).

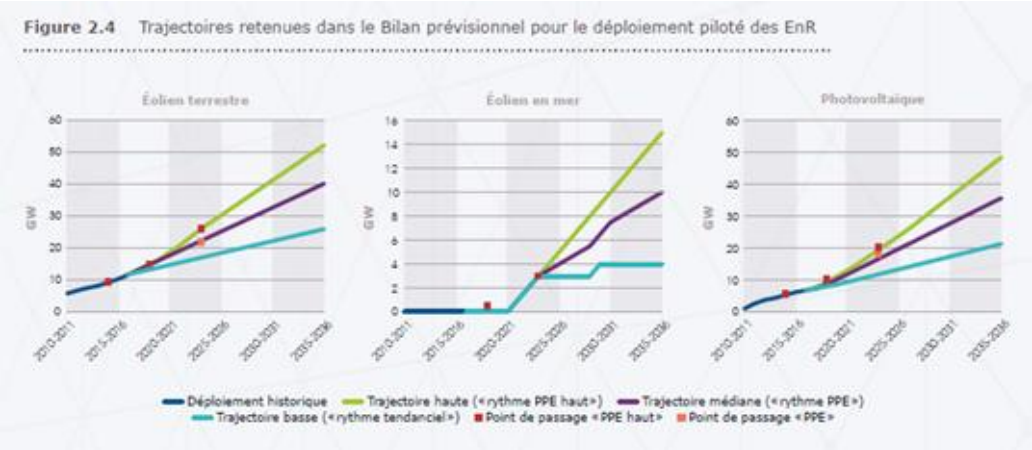


Figure 6: Trajectories for VRE in France. Source : RTE adequacy report, 2017.

At the European level, renewables have been a feature of the power system for many decades, in the form of hydroelectricity. The countries with the highest proportions of renewables today have a mix that is heavily reliant on hydro resources: Norway (96%), Sweden (47%), Switzerland (59%) and Austria (60%).

The power systems of these countries have low carbon intensity (see fig. 7). Countries with higher carbon intensity, usually with limited hydro potential, are turning to VRE generation, in the form either of wind or solar power or a combination thereof, in a bid to lower CO_2 emissions from power generation: for example, Germany, Ireland, Denmark and Spain. However, reducing CO_2 emissions through massive VRE development greatly depends on the generation mix, and may not be immediately successful. France stands out in this regard, with carbon intensity comparable to countries with large hydro resources with only about 10% hydroelectric generation, thanks to the development of nuclear energy combined with renewables.

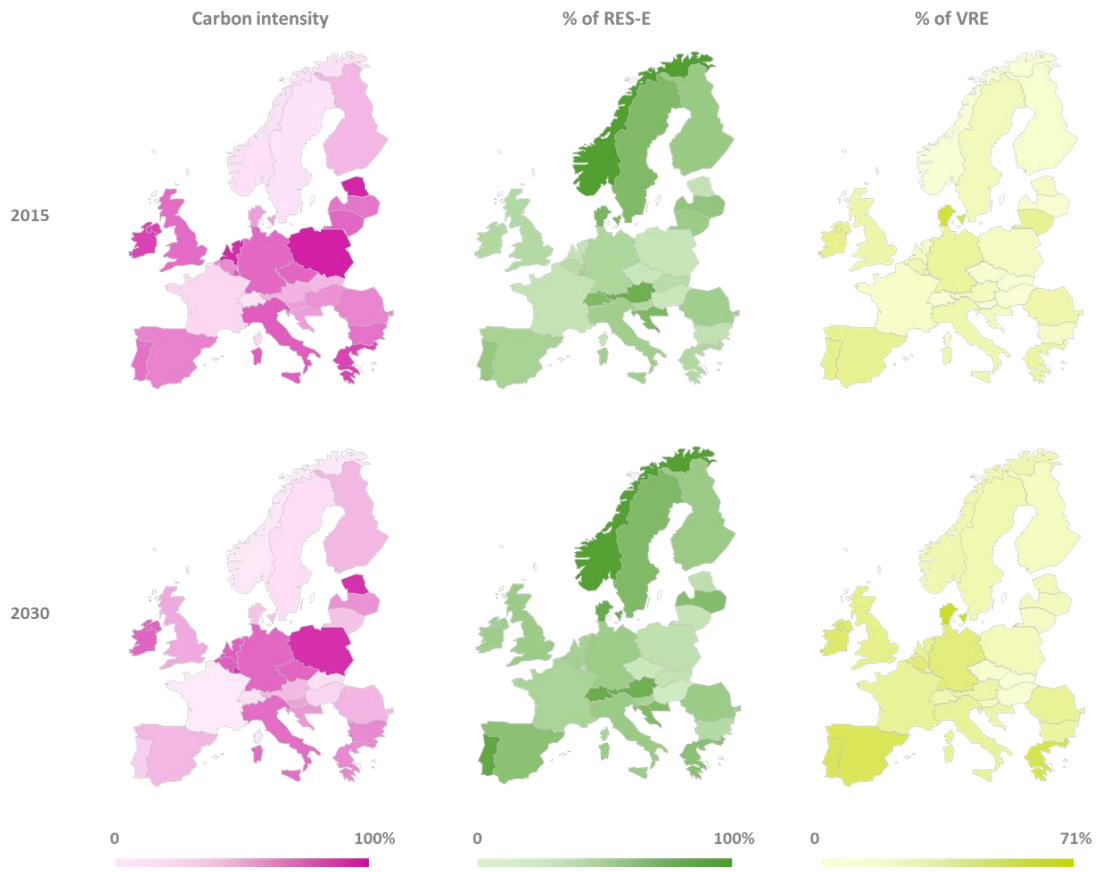


Figure 7: Left – percentage of non carbon-free production in total country generation; Middle – percentage of RES production in country generation, Right – percentage of Variable Renewable Energy production in country generation.
Source: 2015 - EIA.gov, 2030 – EU Reference Scenarios (2030).

For the next decades, the European Commission has set targets for the reduction of CO2 emissions and the development of renewable energy to help the EU achieve a more sustainable energy system. Targets for 2020 are binding and call for a reduction of 20% in carbon emissions compared to 1990, a 20% share of renewable energies in the final gross energy consumption, and a 20% gain in energy efficiency. Targets for further horizons call for a reduction in CO2 emissions of 40% by 2030 and at least 80% by 2050 compared to 1990, and a renewable energy share of 27% in the final gross energy consumption by 2030. This last target is under discussion and might be increased to 32%, but the focus is mostly on the heating and transport sectors.

For the power sector, a set of European reference scenarios, taking account of European targets and policies agreed upon at EU and member-state level, were developed in 2016. They include ambitious development of solar and wind power across Europe through 2030, with most European countries able to lower their CO2 emissions by 2030. Therefore, the share of VRE is increasing in every country, changing the landscape of the power system. France's neighbors will be net importers by 2030 (see fig. 8), while France, with its renewable capacity and nuclear fleet, will continue to export a large volume of competitive low-carbon electricity.

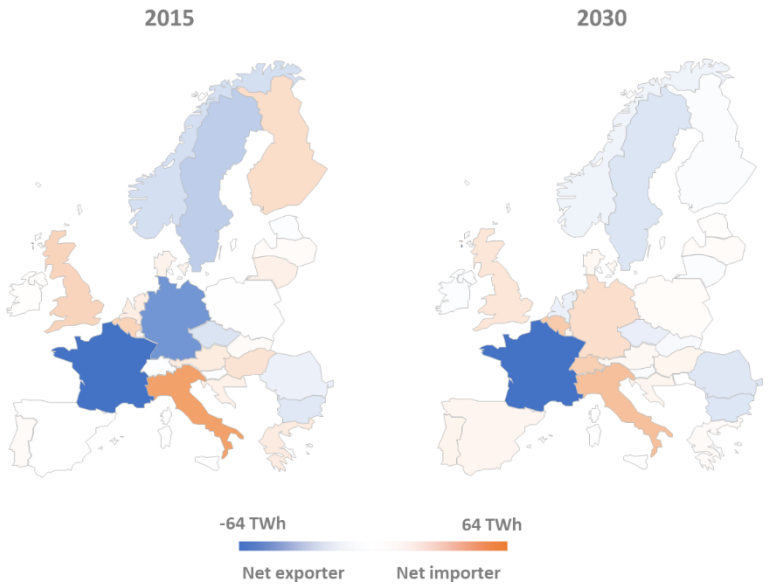


Figure 8: European-wide yearly net exchange balance (Source: 2015 – eia.gov and 2030 – EU Reference Scenarios 2016)

III.C. MERIT ORDER

The term "merit order" refers to the order in which the electricity market uses the various sources of electricity production. Use of the fleet's various components is managed by giving priority, at any given time, to the generation type offering the lowest variable costs: non-dispatchable production such as wind or photovoltaic solar power, and river hydropower plants are used for base generation, since these resources (river flow, wind, sun) are "free" and lost if not converted into electricity; nuclear plants, because of their low variable operation costs, are used for base and mid-merit generation; adjustable hydropower generation (lakes, pumped storage stations) and the thermal fleet (mostly gas turbines or combined cycles) are used for mid-merit and peak generation.

But, obviously, VRE generation depends on local weather conditions (wind, sun, clouds, etc.), which are not necessarily present when needed. For instance, a sunny day in the summer will show a strong variation following sunrise, and production will be highest at 2 pm: the power increase rate can be as much as 900 MW in 1 hour, which is equivalent to one PWR, and therefore will be dispatched to several NPPs.

A similar situation can occur with wind, in case of peak wind speed. On the other hand, a cloudy day in winter with no wind provides no renewable generation, and "conventional" generation (fossil fuels, nuclear power, etc.) has to satisfy the demand. Nuclear power must adapt to the variations in residual demand.

Therefore, as shown fig. 9, the introduction of a greater share of renewable energies (including hydro) will displace the merit order, shifting away high variable cost units (coal, gas, oil) and putting market price at the level of nuclear generation costs.

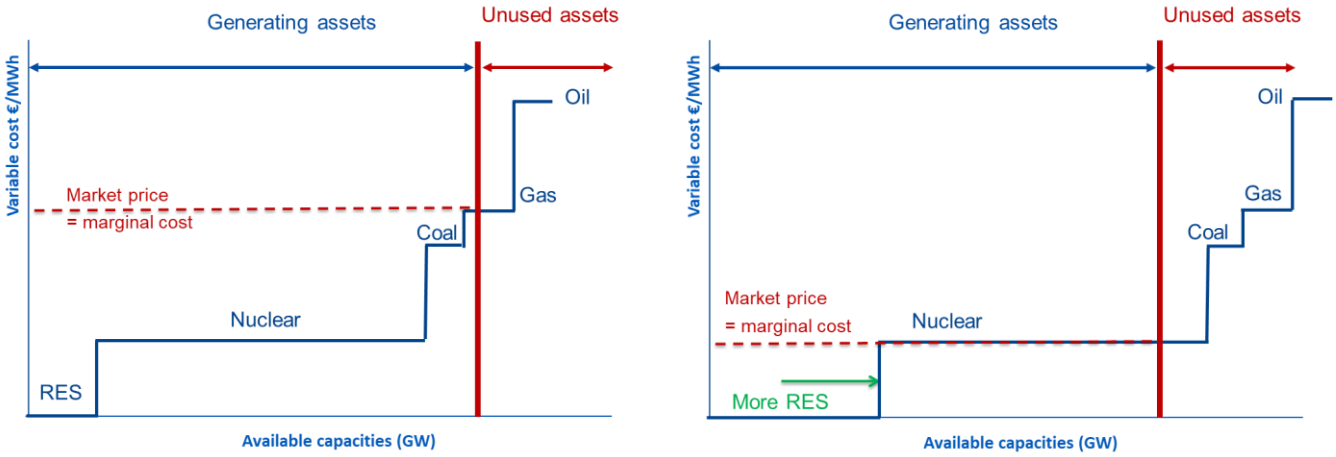


Figure 9. Impact of RES share increase on the merit order

The typical model for pure base-load generation is to produce at maximum power all year long and pay back the costs on the energy-only market by spreading the variable and marginal costs. Today, nuclear plants in France have to adapt to demand variations when net demand gets very low and deviates from the maximum power-only model. Load-following allows nuclear plants to provide ancillary services, for which they are paid: they provide an additional service needed for the stability of the power system. Load-following also allows the producer to optimize the scheduling of refueling operations, thereby giving additional value to the fuel loaded in the core. The periods where net demand is low have a marginal cost for the system that is low. Saving the fuel in the core when the spread is small, usually over the spring or summer, allows the power producer to use it when it is most needed and consequently when prices are highest, usually in winter. This ensures that the largest number of plants are available over the period of highest demand and that no plants are offline for refueling during these periods.

A future with a large volume of renewable wind and solar energy entails a power system with a large proportion of non-synchronous generation. Therefore, complementary services not provided by non-synchronous generation will emerge, and the storage value of fuel will increase. Producers will find new compensations for their base plants. For example, the recent capacity market provides complementary payments to suppliers. In future, massive growth of renewable energy will lead to new services to ensure the safety of the power system, and these services will have payments associated.

One example of new services could be payback for inertia service. The rotational speed of alternators is important to control and stabilize grid frequency. Conventional technologies such as nuclear or hydropower plant alternators comprise heavy rotating masses with high inertia, a physical phenomenon which impedes rapid slowdown or acceleration of rotation. Consequently, they have a very significant stabilizing effect on grid frequency. In contrast, wind turbines, not to mention solar panels, have lower inertia effects. Therefore, a major change in production technology could decrease grid frequency stability, which in turn could lead to a need to reward inertia capability.

Nuclear plants can play a front role in these new services. At the same time, their fuel will be able to provide flexibility to the system, and optimizing fuel use throughout the campaign will allow producers to maximize return.

In tomorrow's power system, producers will be paid for their production from a variety of sources and not only from the energy market. Nuclear plants with their intrinsic characteristics will be a great asset for the power system and its safety.

IV. SAFE AND COST-EFFECTIVE PLANT FLEXIBILITY AT EDF'S NUCLEAR PLANTS

IV.A. BASICS OF FLEXIBLE OPERATION

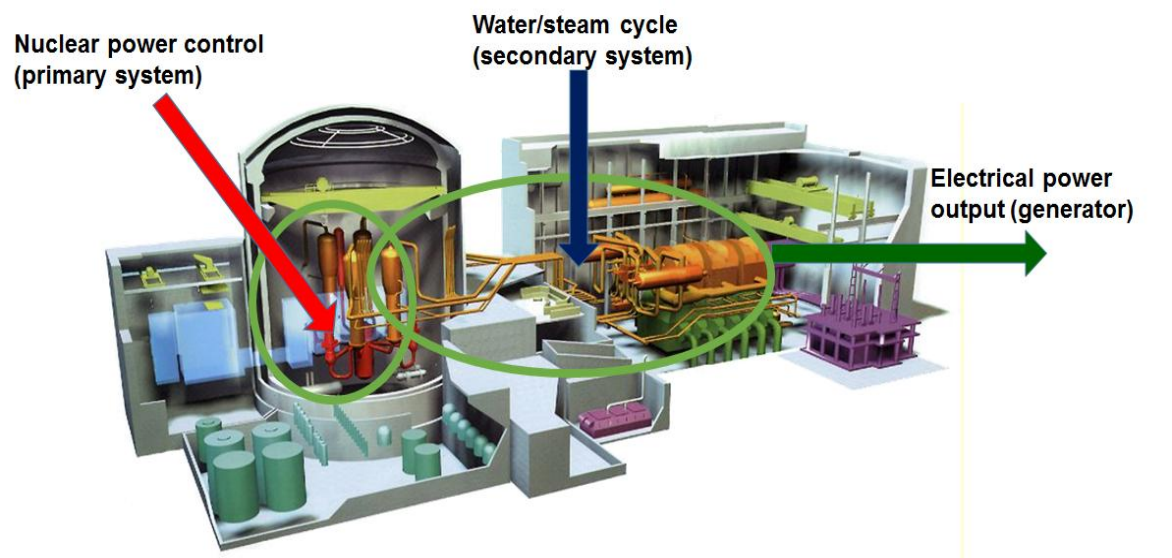


Figure 10. Typical 1,300 MWe unit able to perform power flexibility (power control in the reactor core, water/steam cycle energy conversion, and electrical power output from the generator)

As can be seen in fig. 10, heat generated in the primary water by uranium fission and neutron absorption reactions in the vessel is transferred to a secondary system through a steam generator where water is transformed into steam, which feeds turbines in turn driving an electrical generator. The electricity is then transferred through transformers and lines to the electricity grid.

The nuclear plant's electrical output is controlled by changing the mass flow rate that enters the turbine. To do so, plant operators can vary the steam production from the steam generator, and thus the nuclear reaction in the vessel.

An alternative solution is to maintain constant reactor core thermal power and divert steam away from the turbine through bypass or relief valves to the condenser or the atmosphere. However, this solution has some limitations: potential thermal pollution of the environment, condenser integrity concerns, impaired plant efficiency, etc.

IV.B. CONTROL OF REACTOR CORE THERMAL POWER

Changing reactor-core thermal power, by modulating fission reactions, is effective but has significant impact on core neutronics (flux distribution, burn-up rate, fission by-products), materials (thermal limit) and safety (response to transients). Two main means of reactivity control are used: control rods and boric acid concentration, both being neutron absorbers.

Control rods allow real-time control of the uranium fission process. Composed of materials that absorb neutrons, the rods provide a reactivity margin able to ensure reactor safety, and are used for rapid reactor power changes (e.g., shutdown and start-up).

Compared to the original pressurized water reactors design (Westinghouse's), the main change in EDF's PWR fleet was to adjust the types of control rods and their positions in the reactor core[9].

It is noteworthy that French nuclear power plants (PWR 900 and 1,300) have the greatest worldwide experience in using "grey" control rods specially adapted for plant flexibility[10].

Whereas most nuclear reactors are still fitted with standard "black" control rods, with high neutron-absorbing effect, most of EDF's reactors have "grey" control rods, designed to have lower neutron-absorption, allowing adjustment to local power patterns. "Grey" control rods lessen the deformation of neutron flux distribution that occurs when standard "black" control rods are inserted in or withdrawn from the core. This feature makes them particularly suited to governing core thermal power changes: when power load has to be reduced, several groups of grey rods are gradually inserted.



Figure 11. Control rod

Another mean of controlling core reactivity is boric acid reactivity control. Boric acid is a soluble neutron absorber added to the reactor coolant to provide negative reactivity throughout the fuel cycle, thereby assisting regulation of the core's long-term reactivity. Boric acid control, unlike control rods, ensures an even power and flux distribution over the entire core.

When full power load is stabilized, xenon, a neutron-absorbing fission product, is distributed homogeneously in the reactor core. Xenon is produced by fission reactions (proportional to local power) and builds up and then later decreases, at a certain delay, if the power decreases. Once the power is lowered, the amount of xenon changes, its distribution varying locally: this is managed by injecting boric acid in the primary circuit, to compensate for an overall decrease in xenon concentration, or by dilution to reduce the concentration when xenon levels increase.

Boron dilution explains the reduced amplitude of possible power variations in the last third of the cycle. With the boron concentration in the circuit decreasing along the cycle, it takes more and more water to remove the same quantity of boron. As the flow of dilution is limited, the amplitude of power decreases has to be reduced to manage power changes at the normal pace.

IV.C. CHARACTERIZATION OF LOAD FOLLOWING TRANSIENTS RECORDED FROM 2002 TO 2016

In the following sections, analysis of the impact of flexible operation is based on load-following operations recorded by EDF. We focus on the period 2002-2016, representing 15

years of experience feedback in flexible operation, for which a comprehensive study was conducted by EDF in order to obtain the most representative assessment of the potential impact of large load transients. Two main parameters were recorded: overall load transient duration, and depth of load drop.

Statistical analysis showed that PWR 900 MW and 1,500 MW units presented fewer load transients (respectively, about 40 transients/unit/year and 30 transients/unit/year) than 1300 MW units (average of about 70 transients/unit/year).

Furthermore, the analysis indicated that the great majority of load transients occurred when the fuel cycle (period between two refueling outages) had less than 60% coverage. Only 13% of load transients occurred in cycles with more than 80% coverage.

V. IMPACTS OF POWER FLEXIBILITY ON PLANT SYSTEMS AND COMPONENTS

Feedback from 40 years' experience in reliable flexible operation allows EDF to draw some conclusions about the impact of load-following and frequency control on plant operation and maintenance[11]. The following sections address the main fields (fig.12) that have been assessed.

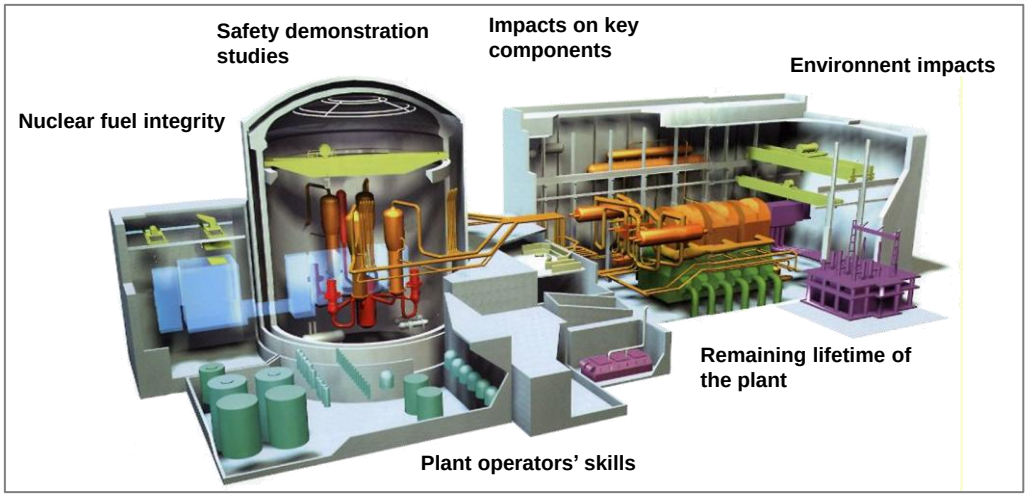


Figure 12. Relevant fields for assessing the safety of flexibility in existing PWR units

V.A. SAFETY FIRST: ADDITIONAL SAFETY STUDIES TO DEMONSTRATE THE SAFETY OF FLEXIBILITY CONDITIONS FOR NUCLEAR CORE INTEGRITY

EDF's studies showed that operating in a flexible mode had no impact on reactor safety, since all variations in power were within areas of operation for which modeling and experimental studies demonstrated the absolute safety of the nuclear core.

This also means that, if any incident occurred during an operation at intermediate load (lower than full nominal power), the reactor could be operated according to existing procedures, and also if the event occurred at full load.

Feedback from EDF's experience shows that safety-risk events (IAEA INES level 0 or 1) due to load-following were rare. No additional LCOs (Limited Conditions of Operation) or SCRAMs (automatic shutdown) were reported due to flexible operation.

For a reactor operating a few days per year at any level of intermediate power, safety studies have to be extended to the full operating power range. The operator must demonstrate that accidental situations would be handled safely regardless of the initial state of the reactor at the time of the event.

Load reduction occurs firstly with partial insertion of rods in the core. The power flux pattern, roughly homogeneous at full load, is then locally modified: less power where rods are inserted, and proportionally more power in areas not reached by the rods. It follows that, if half of the rated power was provided by only a quarter of the height of the core, the concentration of power, and thus the fuel-cladding temperature (or other local parameters) would be locally very high, with a risk of exceeding acceptable limits.

To avoid such a situation, load variation is maintained within an area of operation which ensures that the specified limits are respected at all times.

V.B. ABSENCE OF IMPACT ON NUCLEAR FUEL INTEGRITY

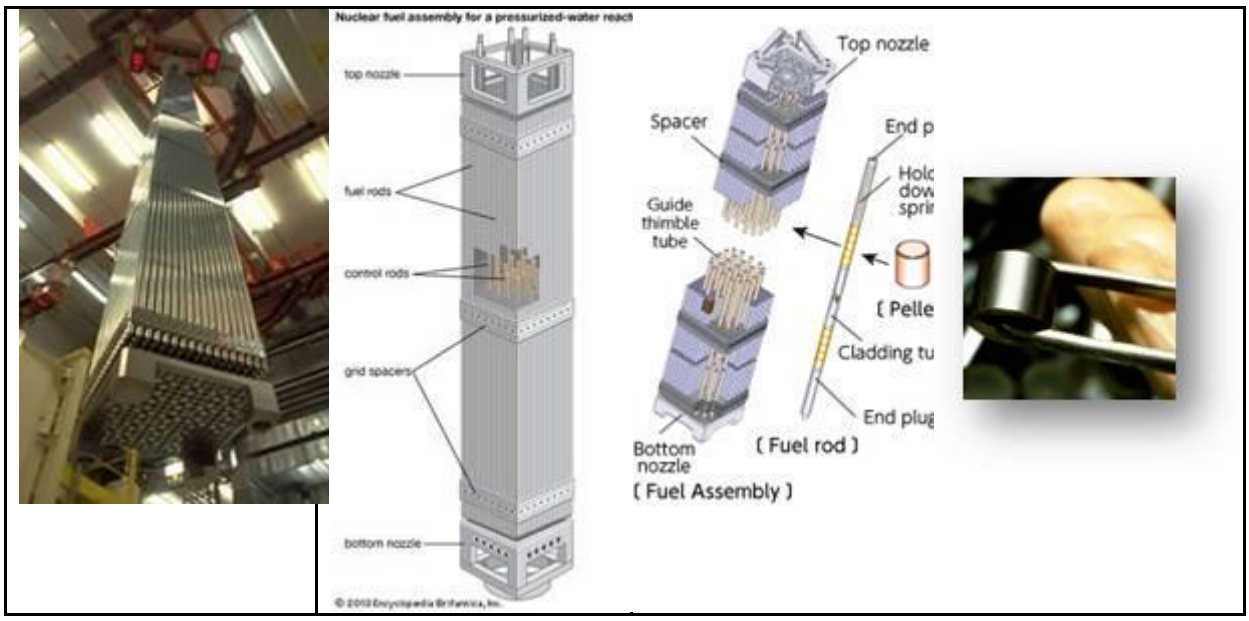


Figure 13. Nuclear fuel assemblies in a reactor core (left), and uranium pellets (right)

A specific safety concern is the phenomenon known as “pellet-clad interaction”. By design, there is a gap in a fuel rod between the cladding and the pellets. Inside the cladding of the fuel rods, there are uranium pellets (fig.13), but also gas: gas deliberately introduced during fuel rod fabrication, but also fission gas generated by the nuclear reactions. When the reactor is operating, fuel pellets expand, and exert contact stress on the cladding. At a given power level, a balance is reached between the external pressure of the cladding (155 bars: i.e., the pressure of the water in the vessel and primary system) and the internal contact stress to the cladding, and the fuel is then said to be “conditioned”. When thus “conditioned”, the fuel can be used for limited periods at power levels lower than the conditioned power level. But, if the power level is kept below the conditioned power level for an extended period of time, clad creeping reduces rod diameter. In that case, if reactor power increases, excessive contact stress between fuel and cladding (i.e., pellet-clad interaction) may occur, and may eventually lead to a crack in the cladding. Subsequently restrictions on power ramp rates and operating times at reduced power must be applied.

Moreover, where control rods are inserted, local power decreases and fuel irradiation is lower. Once rods are extracted at full load, these areas provide increased local power. This increase must remain within certain limits, otherwise hot spots would appear. These limitations are taken into account by using specific credits that are defined for a fuel cycle (period between two unit outages) and followed on a daily basis.

Therefore, EDF has implemented permanent monitoring of the state of fuel conditioning, to ensure sufficient margins in clad stress during power transients. The Operational Technical Specifications thus provide for monitoring of a coefficient, "credit K", corresponding to the available stress margin and determining the number of days authorized at reduced power operation. Specific studies and feedback from years of experience have shown that current flexibility situations do not increase this particular risk in any way as long as credit K remains positive.

The credit is consumed over time if the unit operates with extended reduced power: this is the case for all power decreases exceeding 8 hours over any 24 h period. The credit is reconstituted when the plant operates at base load, over which the primary and secondary frequency controls can be superimposed.

As long as credit K remains positive, contact stress between cladding and pellets is limited. These credits are sufficient to enable changes in power and the introduction of a significant share of renewable energy. The integrity of the first containment barrier is thus not jeopardized by operation in the current flexibility mode.

V.C. NUCLEAR FLEXIBILITY HAS NO IMPACT ON PRIMARY SYSTEM COMPONENTS INTEGRITY

Like the second containment barrier, the primary circuit (vessel, pressurizer, pumps, steam generators and associated pipes) has been designed with mechanical restrictions and a limited number of allowable stress cycles, based on the power changes expected over plant lifetime. The number of transients allowed for a given amplitude is determined by studies, and periodic inspections are scheduled. As long as the circuit has not reached this limit, impact on materials and welds is non-significant.

Reactor thermal power changes during flexible operation result in more frequent variations in reactor coolant system temperature and volume, and in particular in the surge line and pressurizer, where hot water expands and pressure is controlled. While pressure remains stable at 155 bar, temperature varies by more than 30 °C on the side of the hot legs (between the vessel and the steam generator).

Regular cycle counting (counting the number of cycles at an expected stress level, to determine fatigue usage factor) is implemented in EDF's nuclear plants. Each change in temperature exceeding a certain threshold is logged as a situation of transient loading. Throughout plant lifetime, continuous monitoring counts and keeps track of the number of transients, to ensure that the remaining margin is sufficient, by comparing accumulated cycles versus allowable limit. For some specific locations, online fatigue monitoring have been implemented and tested (determining actual fatigue based on measured conditions).

Feedback shows that, in practice, actual power variations since unit commissioning remain well below allowed cycle-counting limits and are fully compatible with vessel aging.

Operating in flexible mode increases wear in control rod drive mechanisms (CDRMs), depending on power variation frequency and amplitude. CRDMs currently used in EDF's

French nuclear reactors were redesigned mechanically to allow for an increased number of rod movement cycles under flexible operation. Cycle counting ensures they are replaced before fatigue failure occurs. After a predefined number of maneuvers, CDRMs have to be changed, with associated direct and indirect costs (components, outage, dosimetry).

No noticeable effect of flexible operation has been detected on I&C (Instrumentation and Control).

V.D. PLANT FLEXIBILITY HAS NO NOTICEABLE IMPACT ON THE ENVIRONMENT

In order to assess the impact of flexible plant operation on the environment, the following issues have been examined: additional waste quantities (solid, liquid, gaseous), effluent temperature and discharge volume, and respect of environmental regulatory limits.

1. Chemistry considerations

One drawback of flexible operation is the increased demand on plant chemistry systems. Reactivity control by boric acid requires the operator to borate and dilute the reactor coolant system frequently. Primary coolant dilution uses large volumes of water, which must be stored and processed before use (to maintain reactor grade purity) and after use (due to presence of dissolved radionuclides) in the primary system. If water is added to the circuit, an equivalent amount must be removed: plant operation thus produces primary effluents, without, however, any additional emission into the environment. These effluents are removed, stored in closed circuits and tanks and treated (gas stripper, evaporator to separate boron from water). Water is first degassed, then distilled to separate boron from pure water. The boron is returned to water tanks for re-injection of into the primary system. The hydrogen concentration in the primary circuit also needs continuous monitoring by the control room operator. Boric acid reactivity control affects reactor coolant chemistry pH. Lithium, in the form of lithium hydroxide (LiOH), is commonly added, to raise primary coolant pH and inhibit corrosion.

Providing this monitoring and good coordination between chemistry and operation is adhered to, no negative impact on chemistry has been noticed in EDF's nuclear plants since the beginning of flexible operation

It is noteworthy that, since tritium and carbon 14 releases are directly correlated to neutron flux, and hence to the energy produced, the total quantity of tritium produced and released in a plant operating under load-following (i.e., not at full load) tends to be less than with a base load unit.

2. Liquid waste and chemical reagent consumption

Feedback from EDF's experience with its fleet identifies two main factors regarding liquid waste volume and chemical reagent consumption: power variation amplitude and the timing of the variation within the fuel cycle. Power variations at the end of the fuel cycle (later than 66%) and at low power (below 45% of nominal power) have the greatest impact. Therefore, planning large power variations at low burn-up and smaller variations at high burn-up is a straightforward way to reduce the volume of liquid effluent due to plant flexibility. Additional volume averaged +20% of the annual volume released by the Nuclear Island Liquid Radwaste Monitoring and Discharge System. Impact in terms of additional radioactivity was undetectable. No impact of plant flexibility on liquid effluent from the secondary circuit, and

hence on consumption of chemical reagents used for secondary-side chemistry control, was identified.

3. Solid waste

With increasing use of boric acid for reactivity control, nuclear units operating in flexible mode require greater volumes of primary water for boron dilution, generating greater volumes of liquid effluent, plus variations in primary circuit pH and corrosion product solubility, and requiring more demanding use of water purification systems circuits, filters and demineralizers.

The impact, but still slight, of flexibility is on the boron recycling system, used for the treatment of primary liquid effluent. This impact was estimated on two types of solid waste: spent ion exchange resins (+5.6% of the average annual volume) and wastewater filters (+3.4% of annual consumption). However, the increase had no impact on waste management (storage, emission limits, transportation or workforce).

4. Thermal Discharge

The maximum thermal discharge of a plant may be limited by a number of factors, including maximum plant outlet temperature, maximum temperature change from plant inlet to plant outlet, and maximum plant volumetric flow rates as specified in environmental permits.

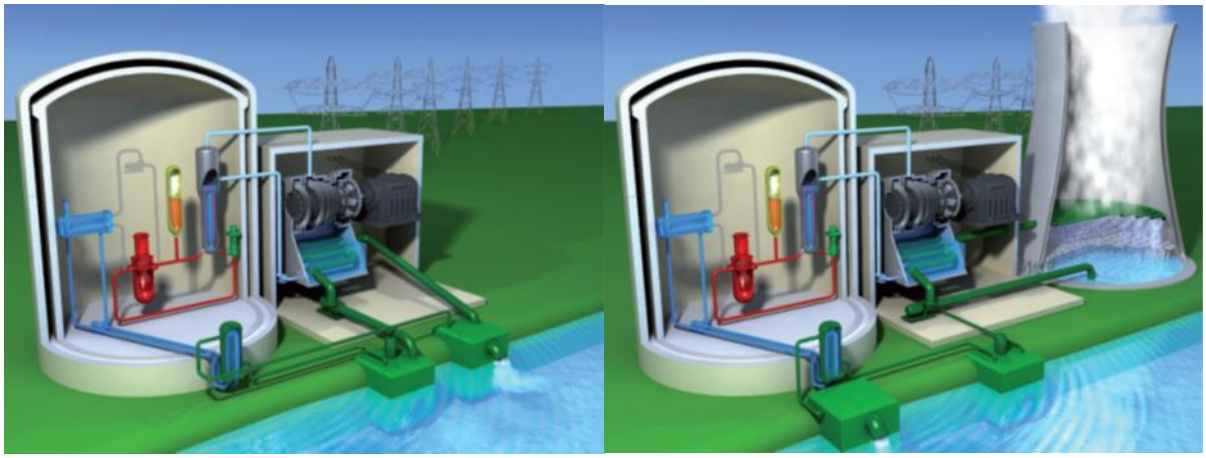


Figure 14. Cooling of a nuclear unit, by river or sea water in an open circuit (left), or with a cooling tower in a closed circuit (right)

Flexible units have less impact on the open environment because they release less heat into the cooling source (river or sea water, in either open or closed circuit: see fig.14). Local conditions vary greatly from one plant to another (depending on river flow, temperature, and season). When the plant is operating under flexible conditions, the unit will obviously release less heat into the cooling source.

The various chemicals used for water cleaning and treatment (e.g., in the condenser, which is the largest heat exchanger with the cooling source) are used in quantities limited by regulations.

5. Environmental Limits

Based on feedback from EDF's flexible operations over the period 2012-2015, an internal study showed that flexible operation had very limited environmental impact, well within

regulatory limits. No noticeable effect was identified for additional radioactivity or operation limitations, even for the most flexible plants (PWR 1,300 MW series).

V.E. FLEXIBILITY HAS LIMITED IMPACT ON THE SECONDARY SYSTEMS

The secondary system (water and steam thermal cycle) consists mainly of heat exchangers connected by pipes, valves and pumps. During variations in load, these circuits encounter variations in pressure, temperature and steam characteristics. Valves open or close, depending on power level. Repetition of these transients can accelerate erosion, possibly including circuit corrosion that can sometimes lead to short unplanned outages. Statistically, comparison of groups operating in load-following mode versus groups permanently at full load shows only very slight differences in performance, and certainly no impact on operational safety. The most noticeable impacts on secondary circuits are leakage at welded joints, erosion of pipes and ageing of heat exchangers.

V.F. FLEXIBILITY DOES NOT SIGNIFICANTLY INCREASE MAINTENANCE COSTS

Feedback from experience with EDF's PWR fleet showed no significant additional costs. From 2000 to 2014, 10 units were deliberately maintained at full stable load (no flexibility periods): in terms of operating performance, the difference between these base-load operated plants and other units operating in load-following mode were within normal scatter: i.e., difficult to evaluate.

Further investigations showed that, since 2010, the load factor unavailability capability in EDF NPPs has remained around 2-2.5 %, 0.5% of which is attributed to flexible operation (as observed for the PWR 900 series).

Statistical studies showed a minimal increase in maintenance costs in EDF units resulting from increased flexibility.

V.G. PLANT OPERATORS' SKILLS ARE CALLED UPON TO MANAGE MORE FREQUENT POWER RAMPS

The ability to operate in load-following mode is part of the control room operator's training and skill.

While control rod positions are determined by power output, water and boron management is ensured manually by the control room operator. The operator's skill is regularly called upon for control of the core. A good understanding of physical phenomena such as changes in xenon, water and boron levels and rod effects is required. As xenon effects are not immediate, the control room operator must be attentive to reactor control several hours after load-following.

To help control room operators, full-scope simulators are used for training, and technical specifications and procedures provide general instructions.

Detailed conditions depend strongly on recent core history. After 3 days at full load, power and xenon are balanced in the core; a power decrease ramp will have simple, foreseeable effects. But, if the reactor shows 3 or 4 variations in the period, with different amplitudes and durations, power profile and xenon distribution will be different.

The next power decrease liable to change these balances should be managed with care; a control strategy must always be defined and adjusted by the control room operators, under the control of the shift manager of the unit. Training courses include this issue, but control-assistance tools have also been developed over the last 15 years. These applications calculate change power flux balance, and allow the operator to better anticipate phenomena and optimize control strategy so as to remain within the center of the authorized area and better predict transient following. Based on recent core history records, these dedicated simulators help control room operators to forecast xenon levels and prepare dilution/borication strategies.

VI. CONCLUSION AND PERSPECTIVES: NUCLEAR FLEXIBILITY IS THE SAFE CO2-FREE SOLUTION TO EXTEND THE SHARE OF RENEWABLES IN FRANCE

While renewable energies have a key role to play in the European strategy for the decarbonization of electricity production, dispatchable generation remains necessary in order to ensure system stability and security of supply. Long term study aimed at understanding the technical and economical feasibility of massive deployment of wind and solar across the European system shows that a contribution of nuclear is necessary in order to obtain the required CO_2 reductions[12].

Flexible operation of nuclear reactors is possible, and has in fact been implemented in France in EDF's fleet of 58 reactors for more than 30 years without any noticeable or unmanageable impact on safety or the environment, nor any significant additional maintenance costs.

Flexible operation requires sound plant design (safety margins, auxiliary equipment) and appropriate operator skills. But three decades of best practices and feedback from a huge experience show that the nominal capacities of the installed fleet (two significant power decreases per day, transitions from 100% to 20% of power in half an hour) are safe and able to balance demand with generation, even with renewables on the grid.

New power plant designs with a larger capacity, such as EPRs, include flexibility features. Studies for future small modular reactors (SMRs, units ranging from 50 to 300 MW) include flexibility features in their specifications.

To remain the leader in very low carbon electricity generation, the EDF group is intensifying the development of renewable energies while ensuring the safety, performance and competitiveness of the existing nuclear facilities and new nuclear investments. EDF announced a plan to increase its portfolio of renewable energy generation by 2030. Investments in renewable energy, with the launch of the Solar Power Plan, represent a significant step towards meeting the Group's goals. By 2035 in France, 30 GW of solar capacity will have been installed with partners. This amounts to quadrupling the country's current solar capacity. In addition to its solar roadmap, EDF has recently introduced an electricity storage plan. EDF will invest to ramp up storage capacity to 10 GW. It is likely that the increase in renewables and storage facilities will keep on challenging the flexibility capabilities of nuclear power plants. R&D studies are on-going on to determine future prospects up to 2050.

Electricity is a key factor for the direct reduction of CO_2 emissions, as well as a substitute for fossil fuels in the transport, construction and industrial sectors. In the forward-looking scenarios limiting global warming to +2°C, low-carbon electricity should thus become the leading source of energy by 2040-2050: the use of electricity should therefore be stepped up, in order to bring down emissions to a quarter of current levels by 2050, and to aim at carbon neutrality.

In this perspective, a strong alliance between nuclear and renewables is a safe, cost-effective and clean solution to achieve a low-carbon generation mix to combat climate change and meet the goal of going beyond the 2°C target set by COP21.

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