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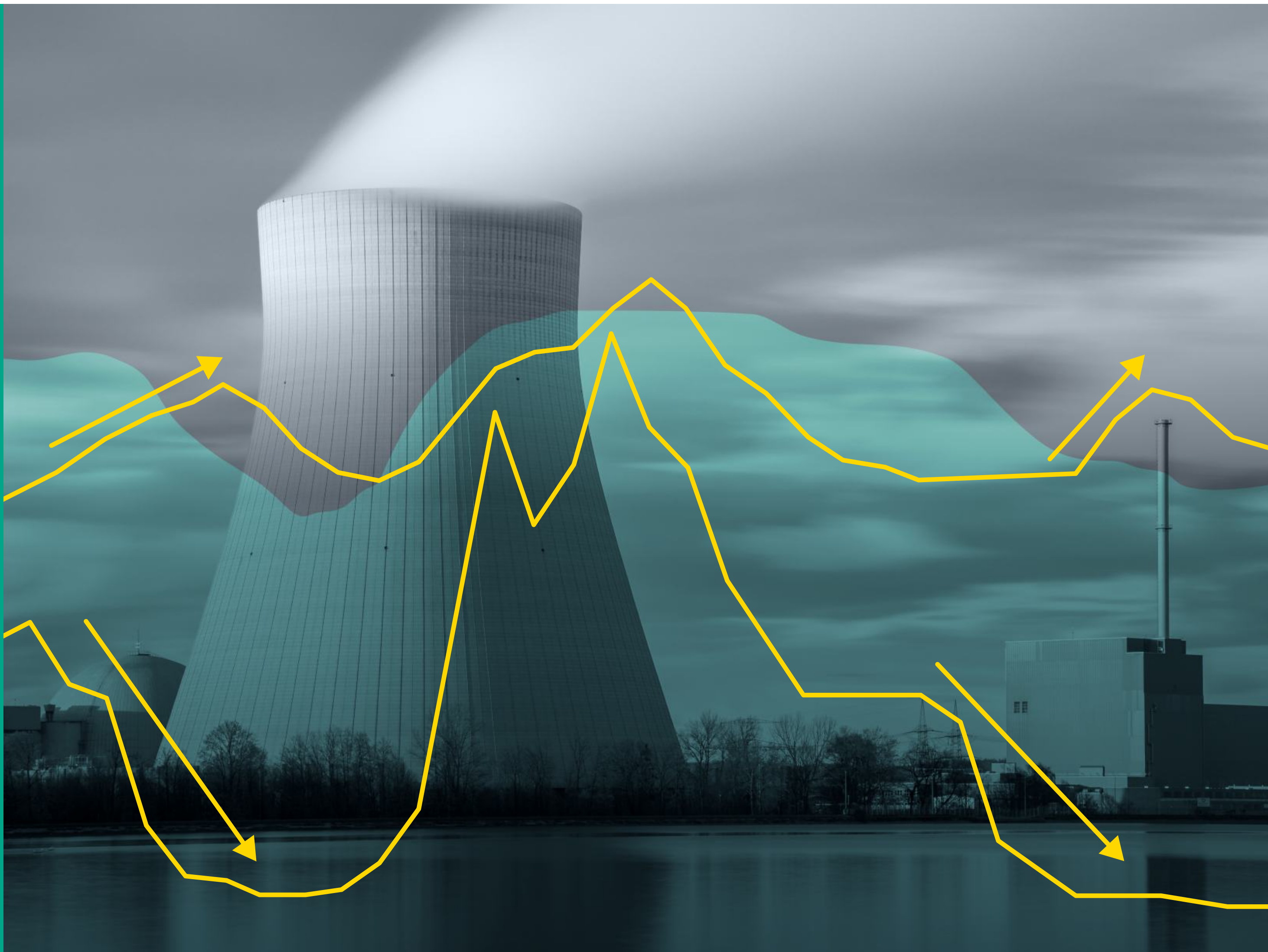
Is nuclear a flexible resource for the power mix?

By Emeric de Vigan and Alessandro Armenia - October 2024



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Executive Summary

This report has a twofold purpose: first, to **introduce nuclear modulation**, highlighting its growing importance and the key factors driving it; and second, to **challenge two traditional beliefs about nuclear energy**: its label as a "baseload" source and the idea that generation has strictly a “load-following” approach.

While it is true that nuclear power has traditionally behaved as a baseload source and not all countries need to modulate, the French fleet challenges the status quo. For decades, France has mastered modulation in its nuclear operations, and in 2024 it boasts the world’s second largest nuclear fleet, with 56 reactors and 61 GWe of capacity. Today, **the fleet continuously shows its ability to ramp down 12 GW in under a day, a 20 % flexible output of its total operational capacity**. A single reactor is able to reduce output by as much as 1 GW, as seen in the case of Cattenom 2 and 3. Moreover, the age at which nuclear plants modulate does not look like an issue: the Tricastin nuclear site example shows that plants built as far back as the 1970s can still adapt to modern modulation practices. If the world’s largest nuclear fleet can do it, why shouldn’t other countries be able to achieve the same?

The second challenged assumption is that nuclear modulation follows a purely "load-following" approach. Our analysis and study cases suggest that modulation is influenced not only by demand but also by **market price signals, which act as proxies for residual demand and cross-border flows**. When residual demand and price decouple amid low prices, nuclear generation is more responsive to price movements.

However, while modulation offers significant benefits, it must be applied carefully. Thermal stress and corrosion remain concerns, as learnt during the 2022 maintenance crisis. Effective strategic planning is crucial to avoid the pitfalls of poorly timed modulation or maintenance, such as the low capture rates seen with the Paluel 4 reactor in May 2024. Moreover, **excessive coordination in modulation could disrupt price formation and shift the market equilibrium**, especially when driven by strategic trading of energy assets.

Introduction

Historically, nuclear power plants were designed to operate at or near their rated power output, providing significant and stable contributions to the grid as baseload sources of energy. The main reason for this is that operating a nuclear power plant at the rated power level is simpler and more efficient. **However, the rapid surge in renewable energy is disrupting the existing equilibrium.**

Figure 1: EU-27 renewable energy installed capacity

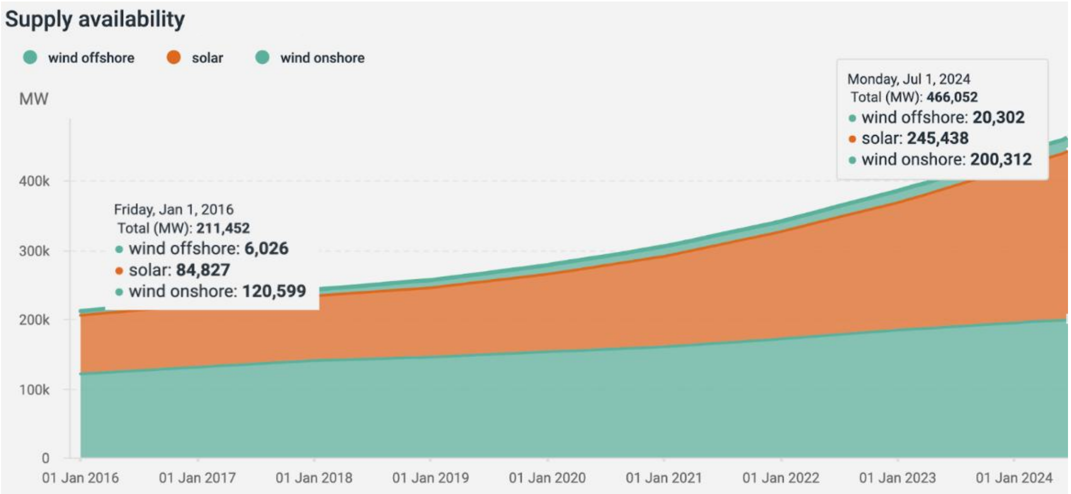

Figure 1 illustrates the EU27 growth in installed renewable capacity. Since 2016, solar installed capacity tripled and wind capacity increased almost 75 %. In July 2024, wind and solar generation accounted for 29 % of the European Union electricity mix. That means **nearly one-third of the power mix is sourced from intermittent sources**.

Due to the merit order mechanism in power markets, most renewable energy producers still lack incentives to reduce output. Benefitting from green subsidies like feed-in tariffs, Guarantees of Origin (GoOs), and Contracts for Difference (CfDs), along with their near-zero marginal costs, renewable producers can place negative bids to stay in the market. This environment, combined with lack of grid flexibility, renewable cannibalization, and low residual demand, has driven down wholesale prices and increased negative price formation. Given the above, the practice of adjusting power output with respect to wholesale prices became more relevant. As a result, the nuclear fleet became more flexible and modern nuclear power plants are capable of operating in various modes.

According to Kpler Power data, nuclear power contributes 24.8 % to the total power mix of the EU 27 in 2024. That is, **one out of every four electrons generated in the EU 27 comes from nuclear power plants**. Pressurised Water Reactors (PWRs) are the most widely used nuclear reactors globally, but there are other reactor types, including Boiling Water Reactors (BWRs), CANDU (Canada Deuterium Uranium) reactors in Canada, and European Pressurised Reactors (EPRs). EPRs, an advanced third-generation reactor technology, were developed by the French company Framatome (formerly Areva) in collaboration with Siemens.

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Currently, the operational EPR reactors include Olkiluoto 3 in Finland, officially inaugurated on September 28, 2023, and Taishan 1 and 2 reactors in China, which started operations between 2018 and 2019. EPRs are designed with enhanced safety features, improved efficiency, and longer reactor lifetimes, positioning them as a cornerstone in the future of nuclear energy development. Despite facing significant delays due to technical challenges and escalating capital costs, EPRs are expected to lead the next generation of nuclear reactors. Alongside, small modular lead-cooled fast reactors are gaining traction in the market, spearheaded by the Italian Newcleo, which is based in France and has raised over €400 million to develop this technology.

All commercial nuclear reactors in France are of the PWR type, but France is planning to shift to EPRs. For example, the new EPR reactor Flamanville 3 could now start up for the first time in 2024, while Penly, Bugey and Gravelines have been chosen as three sites for the launch of the program of 6 new EPR2 technology reactors in France. Flamanville 3 will consist of an EPR-type pressurised water reactor with a 1.6 GW in the pre-operational phase. Once operational, it will become a major addition to France's nuclear fleet. France is also set to launch small modular reactors in 2030, with the UK following in 2032 with a 200 MW plant.

Figure 2: Nuclear generation vs day-ahead prices in May 2024

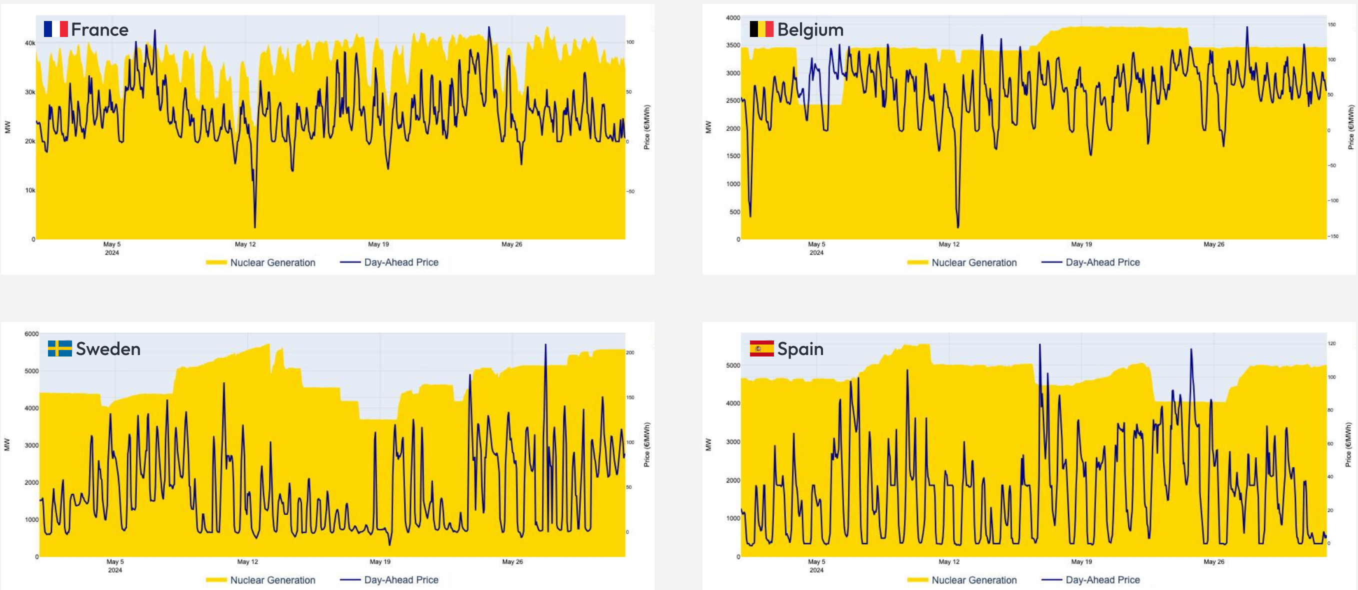

Figure 2 illustrates nuclear production patterns in France, Belgium and Sweden during the month of May 2024. To best observe modulation we must go at an hourly scale. France is the best example of modulation practices. The total generation adjusts almost every day in May, ramping down almost 12 GW Saturday 11th of May from 5-11 AM. On the other hand, Spain is a great example of nuclear use as baseload source, ramping up and down only in case of outages. In Belgium and Sweden instead, we observe sporadic modulating activities. The few times plants modulated in Belgium and Sweden, market prices had dropped into negative territory.

For example, in Belgium nuclear production ramped down 300 MW when prices plummeted to -139 €/MWh on Sunday May 12th. Sweden ramped down around 700 MW on Monday May 14th and a further 1 GW starting from Saturday May 18th due to prolonged low prices in the 4 Swedish bidding zones. At other times, aside from planned outages that feature a clear ramp-up or down, the fleet operates at a constant output.

When mentioning nuclear power, France always comes up. To understand why nuclear power is so relevant to the French context, it is important to take a step back. France decided to develop its own nuclear fleet following the oil shocks of the 1970s, aiming for energy independence. This decision taken more than 50 years ago has had a lasting impact on the electricity market up to the present day. Currently, out of 124 nuclear reactors in Europe, 56 are located in France. Nuclear energy is the primary source of electricity for French consumers, and EDF operates the entire nuclear fleet. Since January 2024, Kpler Power data indicates that nuclear power accounts for 68.3% of the French electricity mix.

For countries desiring to significantly increase renewable energy sources or with high nuclear shares, the question arises as to the ability of nuclear power plants to follow price on a regular basis, including daily variations of the power demand. Before delving into the factors driving modulation, **what exactly is modulation? How do plants perform modulation? What are its benefits and drawbacks? Why is the trend increasing? Are modulation practices disrupting conventional beliefs on nuclear plants?** This article aims to introduce the practice of modulation, provide answers to common questions about nuclear modulation, and present some use cases to challenge the status quo of nuclear activities.

About nuclear modulation

What is modulation?

Nuclear modulation refers to the process of adjusting a nuclear power plant's output in response to market signals or operational constraints.

Figure 3: Yearly nuclear generation in France

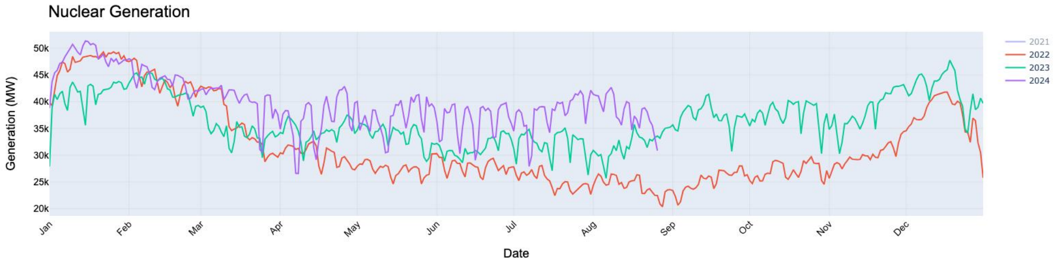

Figure 3 shows French yearly nuclear power generation trends since 2022. **On a yearly scale, generation is higher in the winter and lower during summer months.** On a weekly scale, power fluctuations can ramp up to 15-18 GW driven by reduced weekend demand. Also on a daily level nuclear output demonstrates considerable adjustment, as seen in Figure 2. **Daily fluctuations can not be attributed to routine maintenance operations**, as even the fastest maintenance processes would typically require around two weeks of downtime. This strongly suggests that the observed spikes are a result of deliberate modulation, where power plants are dynamically adjusting their output.

These changes in nuclear output across the years reflect an increasing reliance on modulation, where the frequency and magnitude of output adjustments are notably more extreme. In 2024, the modulation phenomenon is particularly pronounced, as the purple line shows fluctuations of over 10 GW within a single day. This distinctive pattern resembles "shark teeth" due to the sharp and frequent changes in power output.

How do power plants modulate?

When modulating nuclear plants slow down reaction rates in the reactor core. To do so, nuclear plants recur to control rods or boron injections in the coolant. They primarily use neutron absorbers such as boron to decrease the neutrons available for fission reactions, thereby reducing the reaction rate. Other effective neutron absorbers include xenon, cadmium, and hafnium. However, boron is the most abundant and cost-effective option. Control rods are neutron-absorbing rich rods inserted from the top of the reactor core: lowering the control rods absorbs more neutrons, decreasing the fission reaction and power output. Another way is to inject boric acid, allowing it to dissolve in the coolant. By adjusting the concentration of boric acid, the boron injection allows operators to fine-tune the reactor’s power level.

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Nuclear reactors are designed to ramp their power output at rates typically between 1-5% of their maximum capacity per minute. For instance, **a 1 GW nuclear reactor could reduce its output by approximately 600 MW per hour**. Advanced reactors like European Pressurised Reactors (EPRs) offer more flexibility, potentially modulating at rates higher than 5% per minute. A plant's start-up time is classified based on the duration since shutdown: hot starts occur within 8 hours, warm starts between 8 and 48 hours, and cold starts after more than 48 hours. While nuclear cold starts can take less than 24 hours, hot starts allow reactors to ramp according to the aforementioned rates.

Compared to other energy sources, gas turbines, coal plants, and hydropower exhibit distinct operational characteristics. According to **Gonzalez-Salazar et al.**, gas turbines can achieve hot starts in as little as 4 to 45 minutes, while cold starts may take up to 250 minutes. Among fossil fuel-based plants, Combined Cycle Gas Turbines (CCGTs) are known for their rapid ramping capabilities, adjusting at rates of around 20% of full load per minute. Hydropower, with ramping rates of 15-25% of full load, offers even greater flexibility. Pumped storage hydropower, in particular, can start up in less than 10 minutes, making it one of the fastest and most flexible generation sources.

In contrast, coal power plants are much slower to respond. At power outputs above 100 MW, coal power plants have cycle times that are 2.5–2.8 times longer than those of gas turbine combined cycles. Hot starts take between 100 and 300 minutes, while cold starts can extend up to 900 minutes. Depending on the type, their ramping rates lie within 0.5 to 8% of full load. In general, technologies that rely on heat transfer, such as coal plants and combined cycle plants, are more affected by shutdown duration before restart than other technologies.

Despite nuclear reactors having the capability for automatic modulation, regulations in many countries prefer to maintain a manual control approach to ensure stringent safety and reliability standards and automatic load following is often seen as adding complexity to safety management. The EUR (European Utilities Requirements) states that modern nuclear reactors must implement significant manoeuvrability and, in particular, be able to operate in “load-following mode”. To start operating flexibly, baseload running plants may need to consider modifications to support frequency control that depend on plant design. France is a notable exception, where automatic load following, also known as ALFC (from the German “adaptive reactor power control system”), is widely practised and integrated into grid management. The French power mix is dominated by nuclear power, with a total nuclear installed capacity of 61 GW and continuously supplying production within a range between 30 to 50 GW every hour, depending on seasonality.

Figure 4: Ramp down frequency (left) and cumulative normalised ramp down (right) per French nuclear reactor since January 2023

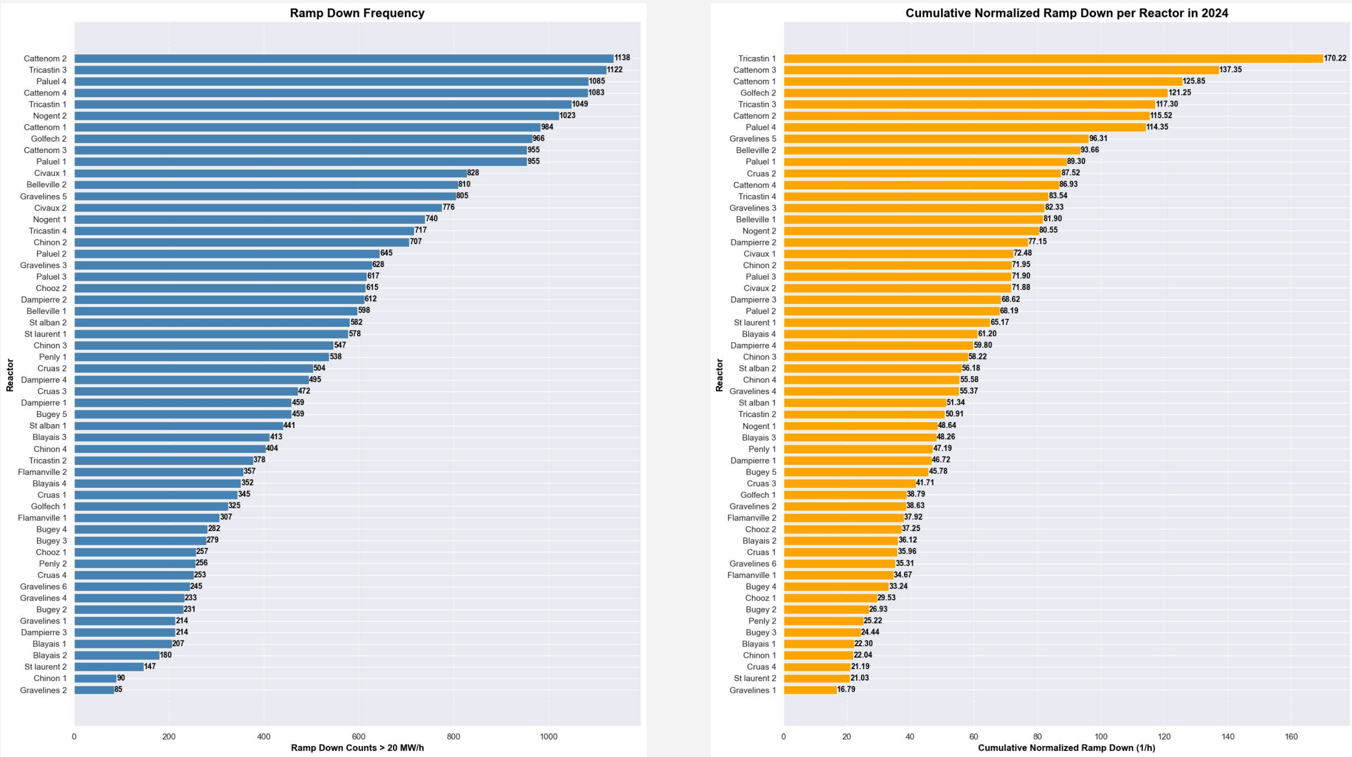


Figure 4 provides a comparison of the operational behaviour of France's 56 nuclear reactors in 2024, focusing on their power modulation patterns. **The blue chart illustrates the number of ramp-down occurrences, defined as reductions in power output greater than 20 MW/h. It highlights the frequency with which each reactor adjusts its power.** Ramp downs exceeding 400 MW/h were excluded, as this threshold was empirically identified as the point above which ramp downs were typically associated with outages. On the right side, **the orange chart illustrates the cumulative normalised ramp-down, which measures the magnitude of nuclear ramp downs, adjusted relative to the maximum capacity of each reactor.** This metric provides insights about the modulation intensity carried by each reactor.

Since January 2023, the average (cumulative and normalised) ramp-down intensity across France's nuclear fleet is near 60 1/h. Tricastin 1 stands out as one of the most intense and among the top five reactors in terms of frequency and intensity. The Cattenom plant also emerges as a leader in modulation activity, while the Gravelines nuclear plant stands out as the least active plant modulating. Reactors such as Paluel 1, Paluel 4, and Golfech 2 rank high in terms of modulation frequency and intensity.

In 2022, several nuclear plants were impacted by stress corrosion issues, leading EDF to address these problems across its fleet, including all 12 of its 1,300 MW reactors and the 1.5 GW Civaux and Chooz plants. The graphs indicate that Chooz 1 and 2, Golfech 1, and Nogent 1 exhibited lower modulation activity, both in frequency and intensity. Moreover, the Penly and Flamanville reactors, particularly Penly 2, show very low modulation activity, suggesting that these reactors are primarily used for steady baseload generation. Interestingly, Civaux appears to have fully recovered from its previous stress corrosion issues.

A closer look at the Tricastin plant reveals variability in operational strategy: Tricastin 1 modulates less frequently but with higher intensity compared to Tricastin 3. A similar pattern is observed at Cattenom, where Cattenom 3 adjusts less often than Cattenom 1, 2 and 4 but ranks second in terms of modulation intensity. The diversity across the fleet shows the strategic deployment of reactors, where some reactors are heavily relied upon for dynamic response while others are operated more steadily for baseload purposes.

What challenges and downsides present modulation practices?

Operating a nuclear power plant at the rated power level is less complex as it requires simpler control systems. The main problem is with the steam turbine: **condensation creates droplets behind the turbine blades, which impact them at high speed and cause erosion**. The turbine therefore loses efficiency and is damaged. Other reasons nuclear plants have traditionally avoided modulation include: the **mechanical and thermal stresses caused by thermal cycling, control systems increased complexity, and suboptimal fuel use**.

Temperature fluctuations can reach up to ±30 degrees Celsius, affecting parts of the nuclear plant. These components include the reactor pressure vessel (RPV), fuel cladding, steam generators, turbines, reactor coolant systems, and piping. The RPV is made of steel alloys, while the fuel cladding, the outer layer of the fuel and control rods, is made of zirconium alloys. Alloys such as steel, Zr or Ni-Cr-Fe alloys, are sensitive to mechanical and thermal stresses. Modulation activity increases the “wear and tear” effect, possibly leading to higher and more frequent maintenance costs, other than higher risks for unplanned outages.

Additionally, modulation introduces new challenges in managing reactor kinetics and control systems. Controlling neutron flux and reaction rates via control rods and boric acid injection is complex. Control rods degrade over time due to radiation exposure and thermal cycling, affecting their efficiency.

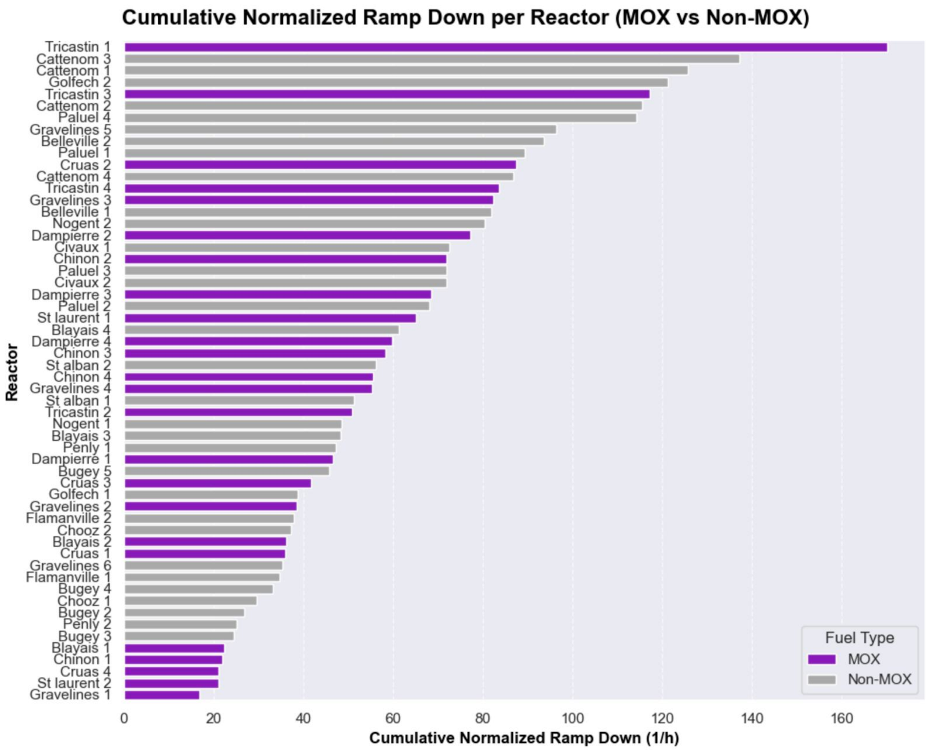
Finally, modulation activities affect the neutron flux distribution within the reactor core. This affects the uniformity of fuel burnup, leading to "hot spots" where some areas of the fuel are consumed faster than others. Frequent adjustments can therefore lead to suboptimal fuel use. Power output changes result in uneven fuel burn. Consequently, more fuel remains unburned and ultimately wasted. Overall, suboptimal fuel use increases the overall cost of fuel per unit of energy produced.

Is there a relationship between modulation and MOX fuel use?

Over the years, advanced processes enabled the recycling of up to 96% of spent nuclear fuel. The key materials recovered are uranium and plutonium, and can be reused to produce new fuel assemblies. MOX, a mixture of plutonium and uranium oxides, is a recycled fuel that recovers the plutonium from spent fuel, thereby reducing waste. According to Orano Group, 1 gram of plutonium recycled into MOX fuel produces as much electricity as 1 metric ton of oil. Orano remains the only company producing MOX fuel assemblies, primarily at its Melox plant in Southern France.

Globally, MOX fuel has been used in 44 reactors since 1972, including 22 in France, 5 in Japan, 3 in Switzerland, 2 in Belgium, and 1 in the Netherlands. Even the Palo Verde plant in the United States, with its three reactors, has the potential to fully transition to MOX, potentially eliminating the need for new uranium fuel by recycling the output from seven conventionally fueled reactors annually. As of 2020, EDF reported that 22 out of its 57 nuclear reactors in operation were using MOX fuel, with an additional 24 reactors authorised to use it. These reactors include Saint-Laurent, Gravelines, Cruas, Dampierre, Blayais, Tricastin, and Chinon. The analysis aimed to determine whether a correlation exists between MOX fuel usage and modulation practices.

Figure 5: Correlation between modulation activities and MOX fuel use



According to our data, there is no correlation between MOX fuel use and modulation practices looking at the nuclear fleet. Nuclear reactor Tricastin 1 uses MOX fuel position ranking 1st, while the last 5 positions are occupied by MOX reactors. This suggests that modulation capability is independent of fuel type, indicating that any plant can modulate, regardless of whether it uses MOX or conventional fuel.

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Why do nuclear plants modulate?

Nuclear power plants modulate their output for different reasons: fuel saving, efficient resource allocation, and cooling constraints. The increasing trend is driven by increased renewable energy installed capacity and market price volatility.

Nuclear modulation ultimately provides higher stability to the grid and enables large-scale deployment of intermittent electricity sources. From any energy asset owner, the aim is to maximise welfare and profitability by optimising fleet management and ensuring highest availability during winter peak. Modulation plays a key role in enhancing operational flexibility. With mindful modulation practices, operators could extend the plant lifetime and postpone refuelling decisions until more data is available, allowing for more informed and closer-to-market choices.

Fuel saving

The key aim of modulation is to align power generation with market demand, not just on an hourly basis, but across monthly and yearly trends. While we've emphasised daily modulation patterns, power plants ultimately structure their fuel cycles to maximise output during the winter months when both electricity demand and prices peak.

Figure 6: Daily nuclear availability in France

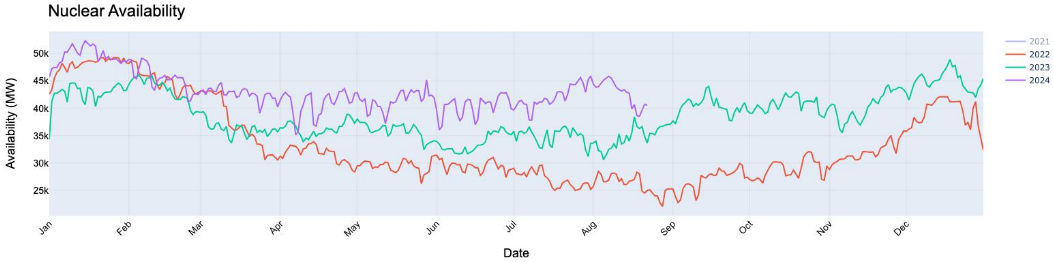

Figure 6 clearly illustrates this: there is an availability gap consistently above 7 GW between summer and winter periods in the last 3 years. This highlights the strategic planning for winter's heightened energy needs. Ideally, refuelling occurs in Q2 and Q3, when demand is lower and market prices suffer solar cannibalization, ensuring full capacity is available during peak winter demand.

Efficient resource allocation - the impact of modulation on capture rates

To fully grasp the benefits of nuclear modulation, it is useful to analyse the French case. Two key metrics used in assessing asset profitability are capture price and capture rate. We will assess the modulation benefits from a macro-level perspective, looking at EDF's fleet, and then delve into the unit's performance at a granular level.

Capture price refers to the average market price that a power generator receives for the electricity it produces.

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Figure 7: Monthly capture prices in France from January 2023

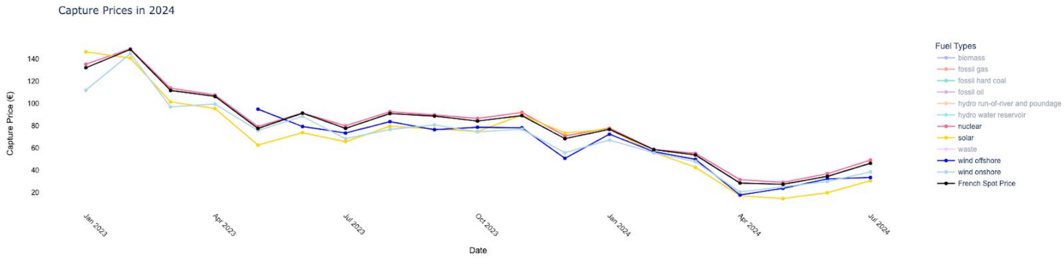
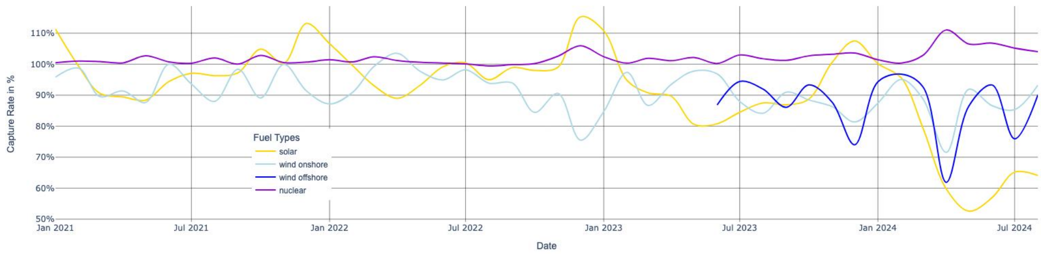


Figure 7 illustrates the French capture prices for wind (offshore and onshore), solar, and nuclear power from January 2023 to July 2024, highlighting significant trends and impacts of renewable energy on market prices. Nuclear capture prices are constantly at the same level or higher of spot prices, while solar and wind prices start to separate starting from April, with a record spread of 18 € in December 2023 between spot prices and wind capture prices. This decline is attributed to the increase in renewables production during spring months' which leads to market saturation and price cannibalization. In 2024, nuclear prices remained robust, often exceeding spot prices, while renewable capture prices averaged 100% lower than nuclear ones.

The capture price is a useful metric to measure the revenue from a specific fuel type or asset, but it doesn't indicate whether the generation unit or fuel type is fully capitalising on market prices. The capture rate, defined as the ratio between the capture price and the average spot price, reflects the asset's performance in capturing market value, expressed as a percentage.

Figure 8: Monthly capture rates in France since January 2021



As seen in Figure 8, capture rates for offshore and onshore wind, solar display distinct trends compared to nuclear. Solar and wind capture rates are volatile and mostly below the 100 % threshold, ranging from 55% to 100% in 2024. This year, renewables capture rates fell below 75% in Q2, with solar and offshore wind dropping respectively to almost 60 % in April. Since then, solar has been under 65 %. On the other hand, nuclear power's performance peaked in April to 110%. As mentioned earlier, spring kicks off a season with more intermittent energy resources, which increases daily price spreads. As shown in graph Figure 3, modulation practices start to emerge at the end of March. The capture rate spread between renewables and nuclear manifest the role of modulation and the flexible nature of nuclear power. In a volatile market environment, flexible assets gain the most.

As we progress, it is valuable analysing when nuclear plants modulate on a daily basis. At what times do nuclear plants adjust their output, and what are the reasons behind it? To do so, we recur to the daily changes in the load factor, where modulation practices are incontrovertible.

The load factor is the ratio of production to availability, indicating the percentage of production relative to the maximum capacity if all plants were operating at rated power. Nuclear plants may shut down due to planned or unplanned outages, so the load factor helps us understand whether the changes in production are due to outages or operational plants modulating.

Figure 9: Average hourly factor in Q2 2024 for the French nuclear fleet

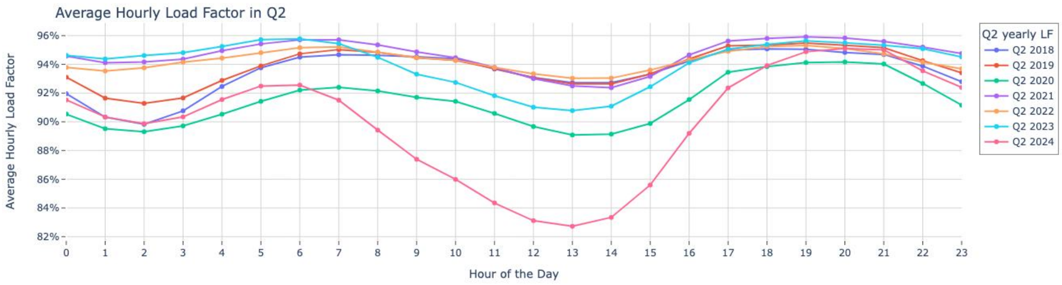


Figure 9 illustrates the average hourly load factor for nuclear plants in Q2 from 2018 to 2024. Several observations can be made from the data: nuclear plant modulation is significantly more pronounced in 2024, with a **10-12% difference in load factor during solar peak midday hours and the evening hours**. This translates to an average cumulative daily ramp down activity of 4 GW per day. **The load factor curve for nuclear plants shows an inverse relationship with the solar curve**, with smaller modulation adjustments occurring in the early hours of the day when demand is low, while the load factor peaks in the evening between 18-21 pm.

The pattern suggests that nuclear plants primarily adjust their output when solar production peaks and/or demand is low, given that solar cannibalization and low demand leads to reduced market prices. Then during the evening nuclear plants ramp up when residual demand is at its daily highest.

To advance our analysis, we aim to quantify the impact of modulation practices by comparing the cumulative ramp-down activities with capture rate per generation unit. This analysis is conducted on a monthly basis and excludes reactors that experienced partial or total shutdowns of seven or more days, regardless whether consecutive or not.

Figure 10: Cumulative normalised ramp down vs capture rate scatter plot for French nuclear reactors in May 2024

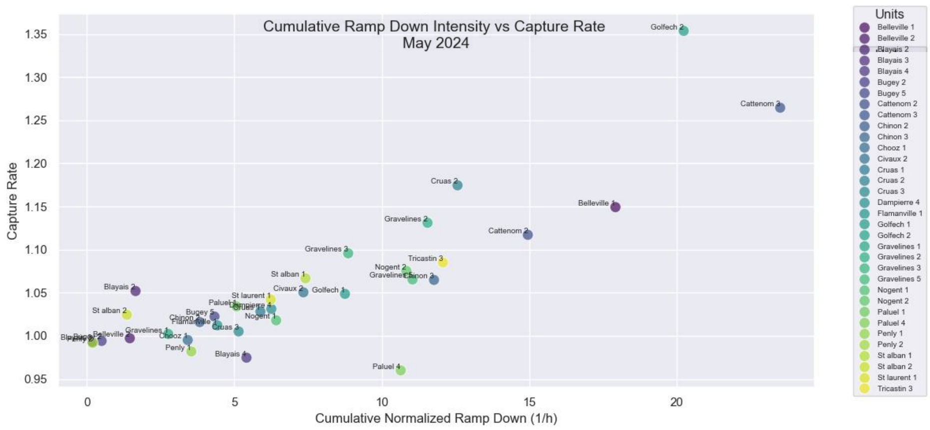


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Figure 10 provides a detailed look at the relationship between cumulative normalised ramp down intensity and capture rate for the nuclear reactors in France during May 2024. From this visualisation, several critical insights emerge about how modulation practices (ramp downs) correlate with the financial performance measured through capture rates.

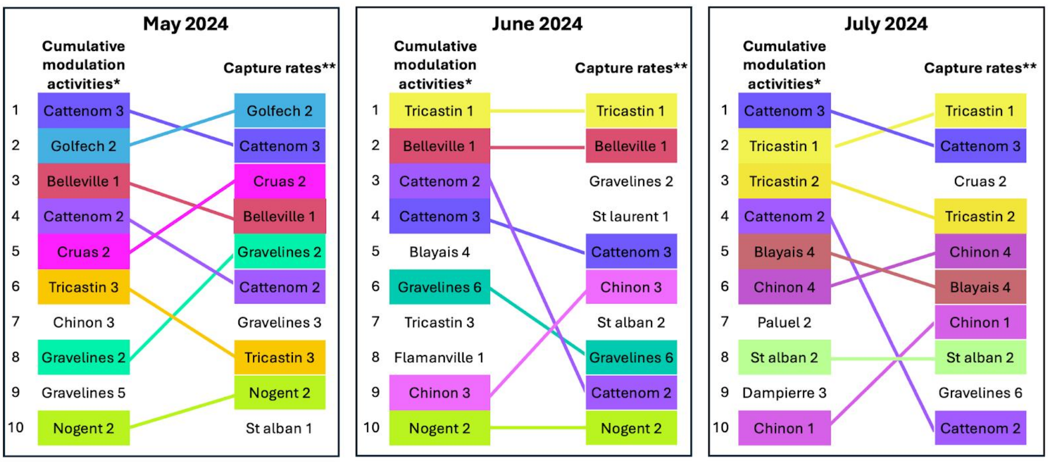
One of the most apparent trends in the data is a generally positive correlation between cumulative ramp-down intensity (in 1/h) and the capture rate. Reactors that exhibit higher levels of modulation intensity tend to display higher capture rates. This suggests that as reactors become more flexible and modulate their output to adapt to grid demands, they can take advantage of market price volatility, which often rewards flexibility, particularly during periods of peak pricing.

While the correlation generally holds, the scatter plot reveals that modulation is not just about intensity but also frequency and timing. Golfech 2 and Cattenom 3 are prime examples. Both reactors exhibit the highest capture rates and modulation activities. However, Golfech 2 shows a lower ramp down intensity than Cattenom 3 yet yields the highest capture rate, possibly due well-timed modulations, enabling it to capitalise on short-term market price spikes. The 2 reactors highlight how intensity, frequency and operational timing are key in determining a high reactor's capture rate. While intensity is highlighted in the proportional trend, frequency and strategic operations play a critical role.

Interestingly, Paluel 4 stands out as an outlier, where increased modulation intensity appears to negatively impact the capture rate. Despite ramp-down intensities of 10 (1/h) or higher, the plant's capture rate drops to 0.96. Notably, the plant experienced a 6-day outage in May, coinciding with a period of high market prices as it was a same-day "planned" maintenance that could have been scheduled during a less critical period. So, one possible explanation is that poorly timed maintenance may have led to inefficiencies.

Also poorly timed modulation practices or maintenance may also occur and lead to inefficiencies. An example of this is Flamanville 1: it scheduled a 2-week foreseen maintenance from September 3 to 17th 2024, while operating during August. In this way, it operated while the average prices in August were 7 % lower than the current averages seen in September.

Figure 11: Top 10 list of French reactors per cumulative modulation activities and capture rates from May to July 2024



Note: the list is sorted in descending order, with 1 being the highest rank and 10 being the lowest.
*Cumulative monthly modulation activities' list is in MW/h, normalized with respect to plant capacity and units with 6 or higher consecutive outages (partial and total) are discarded from the analysis.
**Capture rates per generation unit sorted per descending order, for the considered units

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Figure 11 presents a monthly top 10 list of modulating activities and capture rates out of 56 reactors in France. A key observation is that at least 7 out of the top 10 reactors in modulation also appear in the top 10 for capture rates, indicating a correlation between the two metrics. Notably, the top 2 reactors in modulation are also the top 2 in capture rates. Cattenom 3 results stand out, consistently ranking in the top 5. Tricastin 1 shows exceptional performance, ranking top 2 in both modulation and capture rates for June and July 2024. In August 2023, Tricastin 1 received approval for an additional ten years of operation, becoming the first reactor in France to run beyond the 40-year mark. Interestingly, Cruas 2 in July ranks among the top three for capture rate, yet it does not exhibit significant modulating activities.

Figure 12: Cruas 2 hourly generation profile vs French spot price

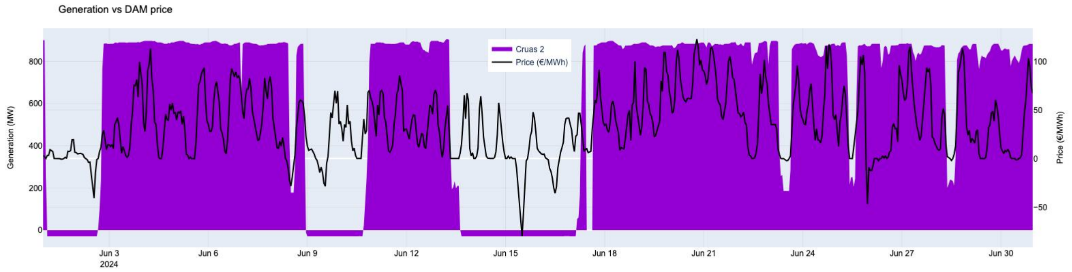

Figure 12 illustrates how Cruas 2 scheduled a 4 day planned outage from the 3rd to the 7th of July, a range in time where the french spot market experienced 20 hours of negative price formation. In the following weeks, the reactor strongly modulated in strategic times where prices went negative. This suggests that not only the frequency of modulation is important: strategic scheduled outages and the intensity of modulation are two critical factors to yield high capture rates.

While the initial observations show a strong link between modulation activities and capture rates, further analysis reveals the importance of strategic modulation aligned with market conditions. The fluctuating rankings of some reactors suggest that operational flexibility, market timing, and efficiency are just as important as frequent modulation when it comes to maximising economic value. We can conclude that when comparing operating plants, modulation activities provide benefits in obtaining higher capture rates and therefore maximising the market value.

Cooling constraints

Nuclear power plants generate heat as a byproduct of nuclear fission, which is used to produce steam and generate electricity via steam turbines. Once it passes through the turbines, the steam needs to be cooled down and condensed back so it can be reused in the system. The cooling mechanism is often done using water from nearby rivers, lakes, or oceans. Power plants typically use techniques like "wet" cooling, where water absorbs heat from steam. The heated water is then either safely returned to its source or cooled down for reuse.

Beginning in the mid-1970s, France developed a large light-water nuclear fleet, strategically positioning them near key rivers, including the Garonne and the Rhône. Currently, six nuclear power plants depend on these two rivers: Bugey, Saint-Alban, Cruas, and Tricastin are located along the Rhône river, while Golfech and Blayais are situated along the Garonne River, with Blayais positioned at its Atlantic estuary.

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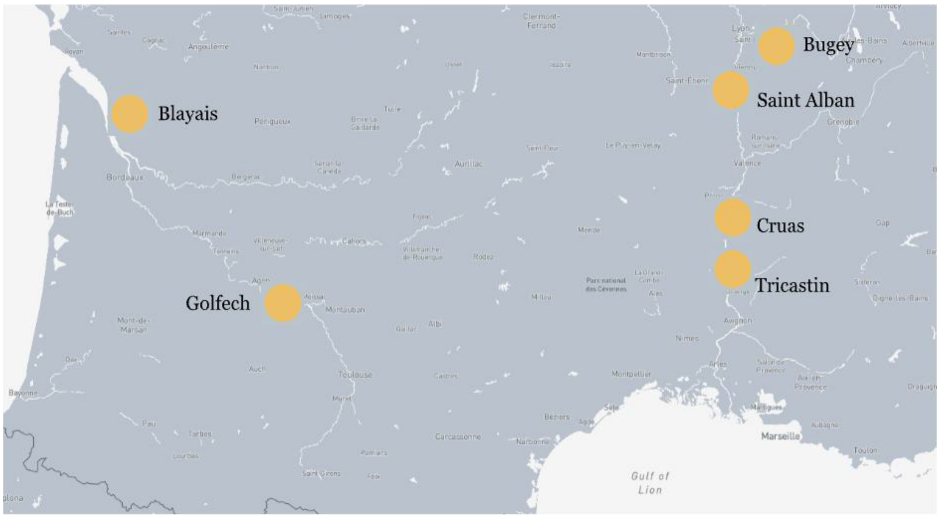
Figure 13: Southern France nuclear reactors' location



Given the reliance on rivers for cooling, the impact of climate change is particularly concerning, as it is expected to increase the frequency and severity of heat-related shutdowns. The major constraint of nuclear curtailment are **environmental laws that regulate the maximum temperature of the water released back to the natural water cycle**. If the river temperature is already high, the additional heat from the plant pushes the temperature above acceptable limits, leading to thermal pollution. To comply with environmental regulations, the plant might need to reduce its output or temporarily shut down. After the 2003 heatwave, France's nuclear safety authority (ASN) set temperature and river flow limits beyond which power stations must reduce their production. The threshold river temperatures that trigger operational restrictions are 26°C for the Bugey plant, 28°C for the Golfech, Tricastin, and Saint-Alban plants, and 30°C for the Blayais plant.

From an operator level, a larger temperature difference between the steam and the external cooling system improves the efficiency of the cooling process, ensuring optimal levels to maximise power output. **Warmer river temperatures reduce the plant's cooling efficiency** and result in the discharge of hotter water from the reactor cooling system, posing a risk to aquatic flora and fauna.

The frequency of nuclear climate-driven outages has increased significantly over the past decade, raising the question of whether climate will consistently lead to summer nuclear plant shutdowns. Since 2018, every summer has seen partial or total shutdowns of nuclear plants due to weather-related conditions. In 2018, several nuclear reactors in France and the Nordic region were forced to reduce power output with elevated sea water temperatures compromising cooling systems. Among the affected plants were Vattenfall's 900 MW Unit 2 in Sweden and Fortum's 1 GW Loviisa power plant in Finland. Since then, nuclear plant alerts and shutdowns have become an annual occurrence during the summer. However, it's important to note that cooling constraints often occur when PV output is high, which helps minimise the economic impact of these shutdowns.

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In 2019, two heatwaves caused unplanned outages at France's Golfech 1 and 2 nuclear plants from July 25th to 28th, and at Golfech 1 on August 13th. Several other nuclear plants along the Rhône River, including Saint-Alban, Tricastin, and Bugey, also experienced shutdowns. The year 2022 was particularly challenging: 26 of 56 reactors were shut down for repairs and inspections due to stress corrosion issues, compounded by four severe heat waves that forced several nuclear plants to reduce power output or shut down entirely. This combination led to record-low nuclear availability, with France's nuclear capacity dropping to around one-third of its maximum for nearly a month.

In 2024, after Golfech ramped down 1 GW at the end of July due to high temperatures in the Garonne River, a second heatwave in August led EDF to alert new potential outages. This resulted in unplanned total shutdowns at Bugey 2 between August 12 and 16 and partial outages at Saint-Alban 2 from August 10 to 15 due to high temperatures in the Rhône River. EDF planned a 2-month outage for Saint-Alban 1 on August 7 with maintenance operations beginning on August 17.

What are the factors driving modulation?

Excluding long term strategies or external factors like climate change, it is important to question whether other factors also contribute to short-term modulation practices. Historically, nuclear plants modulating activities have been described as "load-following". Specifically, these would follow residual demand, which represents the share of electricity demand that must be met by non-renewable sources after accounting for renewable energy production. However, we also question whether nuclear demand is influenced by price signals. The following section will outline the reasons supporting this perspective.

Residual demand vs price correlation

The belief that power plants study price signals stems from the initial observation that residual demand and wholesale prices are directly proportional.

Figure 14: hourly correlation between residual demand and day-ahead prices in 2024 in France

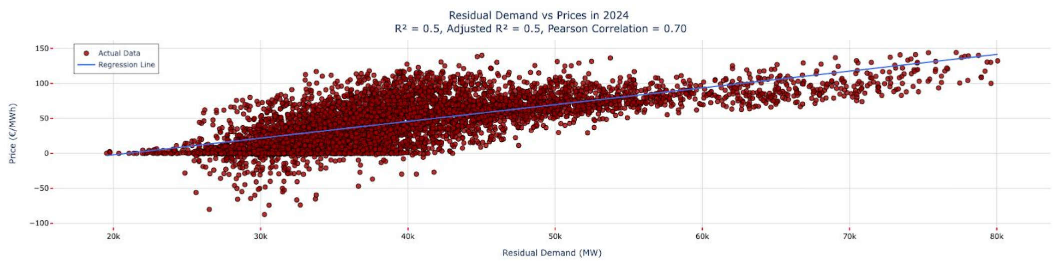

Figure 14 illustrates the hourly correlation between spot prices and residual demand in 2024, resulting in an R squared value of 0.5 and a Pearson correlation coefficient of 0.7. This indicates a positive linear relationship between the variables. Notably, the plot reveals that high residual demand is less predominant to price fluctuations, consistently above 50 €/MWh. Conversely, when residual demand is lower, additional factors come into play influencing price formation such as border flows, weather forecasts, or unplanned outages.

Figure 15: hourly correlation between residual demand and day-ahead prices in Q2 2023 in France

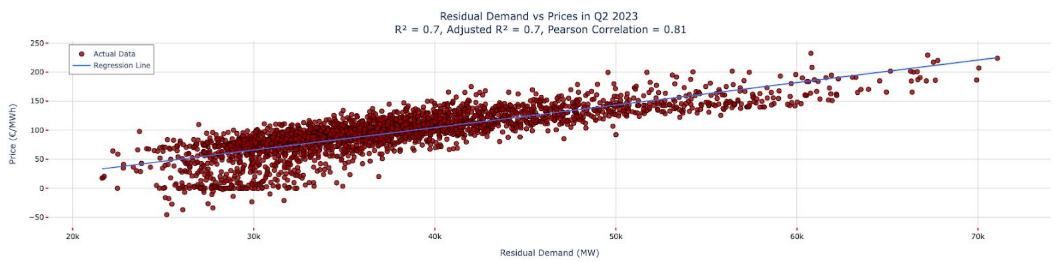

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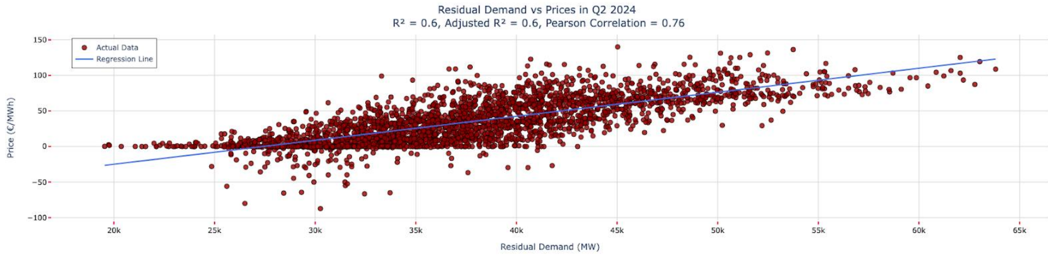
Figure 16: hourly correlation between residual demand and day-ahead prices in Q2 2024 in France



The statistical results from Figure 15 and 16 show how the correlation between residual demand and wholesale prices strengthens in Q2. Interestingly, all scatter plots reveal more data points gathered at the lower end of residual demand, where prices often drop, at times turning negative. This pattern is tied to renewables and particularly solar cannibalization, which is more abundant during the longer, sunnier days of spring and summer.

When residual demand is low, nuclear and fossil fuel plants face fewer opportunities in the wholesale market as renewable energy sources gain more presence, and price volatility increases, often dropping to low or negative levels, making hedging more challenging for market players.

Price forecasting - the clear hedge path

In the energy market, managing risk and ensuring profitability are key concerns for market players, especially during periods of low residual demand. As observed in Figure 13, when residual demand is low, price volatility increases, with the standard deviation leaning towards the lower end of the price spectrum, even going negative at times. This poses a significant risk, as producers may find themselves unprofitable in such conditions, a scenario they must avoid.

To mitigate this risk, it becomes crucial for market participants to have a deep understanding of both their marginal costs and the prevailing market price. Forward contracts serve as the first hedge for energy producers, acting as key benchmarks and providing a foundation for continuous insights into future market conditions. These contracts allow producers to set initial positions, reducing exposure to price volatility in the future.

As the market progresses, wholesale prices offer an opportunity to prepare bids for the day-ahead market, adjusting those bids during the intraday market if there are significant misalignments between announced production and actual output. However, unlike prices, residual demand remains unpredictable until it materialises and can't be hedged.

To address this uncertainty, market players often run price optimization problems the day before, calculating their marginal costs and placing bids aimed at maximising profitability while hedging against potential losses. Profitability tends to peak during times of high residual demand, as these conditions leave space for traditional plants to operate more effectively. On the other hand, energy asset trading becomes a crucial tool to hedge on low price formation, enabling producers to hedge their positions and optimise operations. A key strategy is asset-backed trading (ABT), where organisations that own energy production assets take advantage of market conditions by purchasing cheap energy during low demand periods and ramping down their production to reduce costs while fulfilling contract obligations.

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This practice leverages on the limit order. In energy markets, a limit order is a type of bid where the buyer specifies the maximum price they are willing to pay. If the market price drops to or below that level, the order will be executed. This allows the supplier to control costs and only purchase energy when it meets their predefined price conditions. For instance, when market prices are lower, producers can purchase cheaper electricity from the market instead of generating it themselves, temporarily shutting down their own plants. This allows them to meet contractual energy supply obligations while reducing operating costs. This strategy hedges market volatility and protects asset margins. However, the success of the approach leverages on the flexible nature in power plants, enabling producers to adjust production schedules in response to market signals.

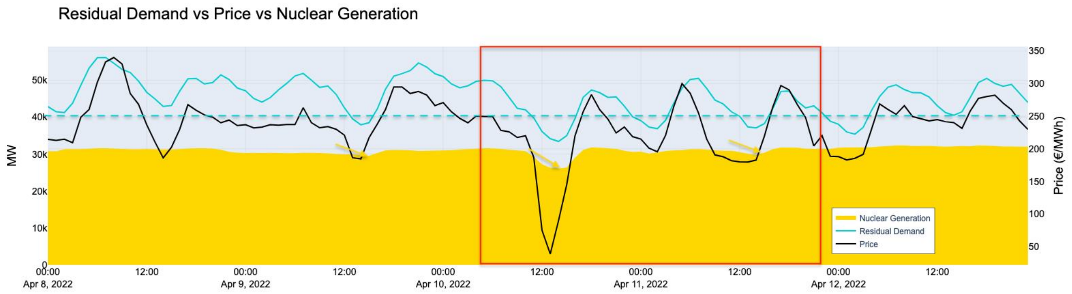
That said, this doesn't imply that market players disregard the behaviour of residual demand. On the contrary, residual demand remains a fundamental factor in their decision-making. However, deviating from it at times can prove beneficial. Price, in fact, often serves as a proxy for both border flows and residual demand, and following price trends can help ensure the ultimate operational goals of power plants.

In the first case study, we present two examples from the 2022 energy crisis. In one, nuclear modulation appears to respond to a residual demand threshold, while in the other, it aligns more closely with market price movements. The second case study illustrates 2 examples in 2024 of how nuclear generation followed price signals in scenarios when price and residual demand were completely decoupled.

Case study 1: 2022 energy crisis

Amid the energy crisis, nuclear generation responded to demand and prices with modulation practices.

Figure 17: Residual demand vs spot price vs nuclear generation line curve between April 10 and April 20, 2022



Focusing on the midday hours between April 10 and 11:

- On April 10th, at 10 AM, spot prices dropped sharply from 220 €/MWh to 38.9 €/MWh within just three hours, prompting a 5 GW ramp-down in nuclear generation.
- On April 11, a brief attempt at modulation was observed around midday but did not fully materialise.

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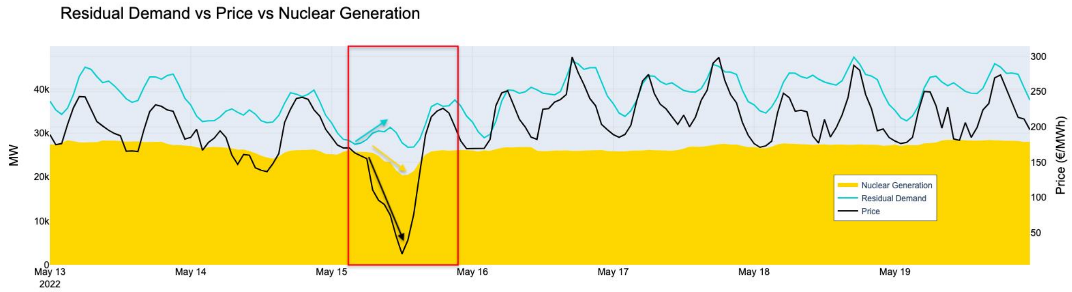
With a 4 GW difference in residual demand between the 10th and 11th of April, one day nuclear ramped down 5 GW, around 8% of the total French fleet capacity, while the following day it ramped down by 1 GW. From empirical observations, it looks like 40 GW is the residual demand threshold below which nuclear modulation is triggered. This suggests that amid high residual demand values, the parameter does play a key role in triggering nuclear modulation.

Figure 18: Residual demand vs spot price vs nuclear generation line curve between May 13 and May 16, 2022



A second example occurred on May 15, 2022, shows the opposite. In a low residual demand environment (below 35 GW empirically for France), despite rising residual demand, prices plummeted from 155 €/MWh at 6 AM to 20.1 €/MWh by noon. In response, nuclear generation ramped down by 5 GW, a significant 20% of the available output at that time. This suggests that price was the key driver in nuclear modulation.

These modulation practices unfolded during a period of sustained high energy prices. EDF's decision to modulate nuclear output suggests that short-term market conditions and price signals were key triggers for operational adjustments.

Case study 2: decoupled price and residual demand curves

Figure 19: Residual demand vs spot price vs nuclear generation line curve between June 20 and June 25, 2024

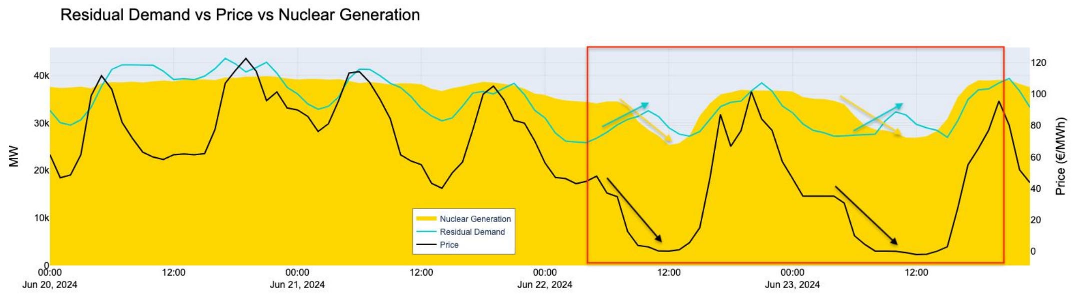
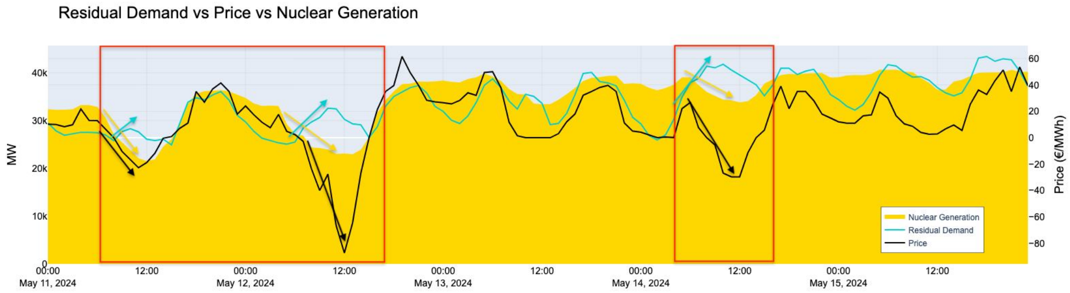


Figure 19 provides a first example of how price fluctuations become significant during periods of low residual demand. During the weekend of June 22nd and 23rd 2024, prices dropped to near-zero levels amid residual demand showing an increasing trend. Nuclear modulation followed suit, ramping down 9 GW and 6 GW. Specifically, on June 22nd, the nuclear fleet modulated 9 GW between 7 AM and 1 PM, despite a 14% increase in residual demand. This highlights the relationship between nuclear modulation and price movements under a certain residual demand threshold and suggests how price can be a key driver during weekend periods.

Figure 20: Residual demand vs spot price vs nuclear generation line curve between May 11 and May 16, 2024



In Figure 20, a similar pattern can be observed in May during the 11-12 weekend, but also during weekdays. In fact, on May 14th, as prices plummeted to a negative - 29.6 €/MWh, nuclear responded ramping down 6 GW amid residual demand increasing. In contrast, the next day on May 15th, nuclear output remained steady during midday hours despite residual demand being 3 GW lower than the previous day, with prices stabilising around 20 €/MWh. During the 14th of May sunny weather caused massive high solar output in the central western region, causing cross-border flows inertia less favourable to France which imported 5 GW from DE and BE. While residual demand is blind, Price here can act as a proxy of both phenomena mitigating risk.

In both examples, residual demand behaved inversely to the price, yet data show that nuclear generation was more aligned with price movements than having a "load-following" approach.

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Conclusion

In conclusion, this report introduced the practice of nuclear modulation, explained the reasons behind its increasing importance and which key factors drive its growth, using France as a prime example. Modulation challenges two popular beliefs: nuclear's label as "baseload source" and the assumption that generation strictly follows load patterns.

Nuclear plants modulate their output for various reasons, including optimising fuel usage before maintenance times, addressing cooling limitations, and enhancing profitability through operational efficiency. While it is true that nuclear power has traditionally behaved as a baseload source and not all countries need to modulate, the French fleet challenges the status quo. Modulation practices have been in place for decades, with the fleet demonstrating today its ability to **modulate up to 12 GW in under a day, that is 20 % of its total capacity**. In Q2 2024, the French nuclear load factor registers a daily **10-12% difference between solar peak midday and evening hours, resulting in an average 4 GW daily ramp down**. The age of the nuclear plant is not an issue: the Tricastin nuclear site shows that plants built as far back as the 1970s adapt to modern modulation practices. Nuclear units are strategically scheduled or adjusted to reduce daily output by as much as 1 GW, as seen in the case of Cattenom 2 and 3. The shift in perspective is timely, especially with China's plans to surpass France in nuclear capacity as it ramps up construction of 26 reactors.

The key drivers of nuclear modulation go beyond traditional "load-following" practices, with price signals playing an increasingly significant role. With residual demand and prices correlating, data from 2024 reveals that price volatility, particularly during periods of low residual demand, influences market dynamics more than demand alone. Our analysis and case studies suggest that modulation is influenced not only by load but also by market **price signals, which act as proxies for residual demand and cross-border flows**. When residual demand and price decouple amid low prices, nuclear generation is more responsive to price movements.

It's crucial to recognize that modulation practices are beneficial when applied carefully. Thermal stress and corrosion issues remain concerns. The 2022 maintenance crisis raised doubts about how modulation may have contributed to the wave of breakdowns. With 26 of France's 56 reactors shut down for repairs and inspections, coupled with a series of heatwaves, nuclear availability dropped to record lows, with capacity falling to about a third of its maximum for nearly a month. Moreover, strategic planning and execution is essential to avoid the pitfalls of poorly timed modulation and maintenances, such as those seen with the Paluel 4 reactor in May 2024. Finally, excessive coordination in modulation efforts could influence price formation and shift the market equilibrium between demand and supply, especially when driven by strategic energy asset trading.

Kpler products

Power market intelligence through a variety of data and analytics tools.

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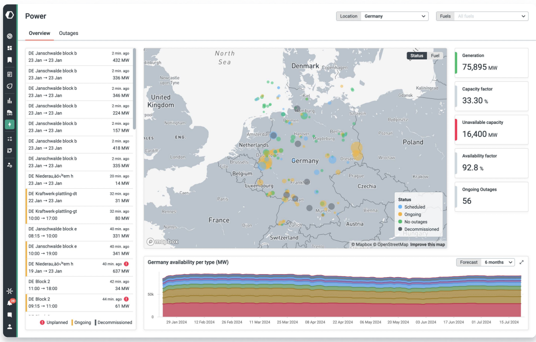
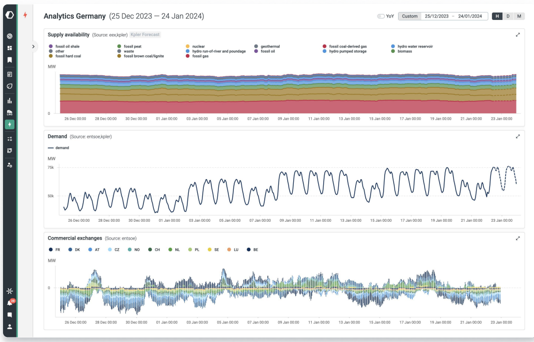
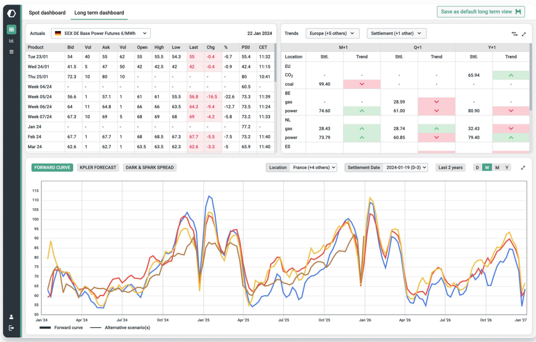


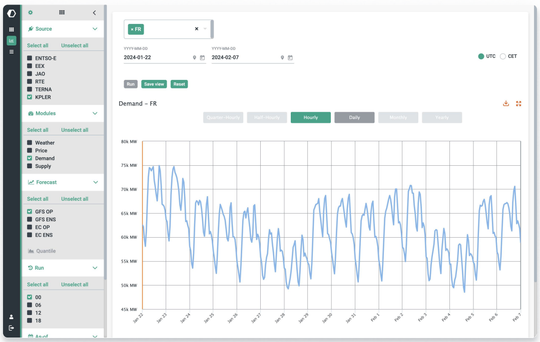
Supply and demand modelling



Proprietary fundamentals forecasts



Post-processed market data



Use cases

- Build better supply and demand models with fuel availability curves, renewable generation forecasts, and demand forecasts
- Ingest robust post-processed market and weather data for building your own models and systems
- Anticipate market movements with real-time outage alerts
- See price trends for power, gas, and carbon to shape procurement strategy
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