

Opening the Automatic Frequency Restoration Reserve Markets in Europe: An Opportunity for Electrolysers

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Abstract

As electricity market liberalization progresses in Europe, more and more coupled ancillary services markets open in different countries. While large industrial plants were in the past already participating e.g. in frequency containment reserves (FCR), the opening in France of the automatic frequency restoration reserve (aFRR) brings with it new opportunities in terms of explicit flexibility revenues as well as related positive environmental impact. Indeed, providing such services with demand modulation allows conventional production means to operate at better efficiency. In November 2023 the aFRR market opened partially in France with the possibility of placing energy bids. Since mid of June 2024, the market is fully open with the capacitive part being operational.

In this paper, Energy Pool highlights the potential of energy flexibilities, both implicit and explicit, the evolving ancillary services market in France and other countries where they operate large industrial assets. In particular, the aFRR market opening and associated price level is discussed. The certification process of industrial assets such as electrolysers is presented: indeed, they are technically suited to operate on these high profitability markets. The associated economic and environmental benefits are documented as well for different electrolysis processes as for e.g. electrical boilers.

Keywords: Electricity market, Frequency containment reserves (FCR), Automatic frequency restoration reserve (aFRR), Energy bids, Electric flexibility, Energy Pool.

1. Introduction

Aluminium demand is expected to grow significantly in the coming decades because of increasing societal wealth, population growth, but moreover because aluminium plays a key role as material for constructing the energy transition e.g. in the needed cables, solar photovoltaic modules or lightweight automotive solutions. Being part of the solution for climate change mitigation, low emission aluminium becomes a necessity since it will decrease emissions during its production phase, but also impact massively the carbon footprint of these climate hazard fighting technologies that consist for a large and subsequently growing part of aluminium. In addition, the massive amounts of aluminium that are required in transport, in the energy sector of generation, storage and distribution or in the building sector need to be available at affordable costs so as not to slow down the pace of deployment of these new infrastructures.

2. Competitiveness and Decarbonization by Activating Flexibilities

The US flexibility resources task force within the Energy Systems Integration Group states in its 2022 report [1] that “Aluminum production ... has an energy intensity of 71 gigajoules (GJ) per ton”, i.e. about 20 MWh while other sources report as much as 100 GJ/t direct energy for the entire cradle-to-cradle energy consumption, even including recycling (6.5 GJ/t) [2]. As such, it

accounts for 4 % of the global electricity demand and 3 % of the global greenhouse gas emissions worldwide [2] with the present mix. As stated formerly, the need for aluminium is expected to grow. According to Fortune Business Insight [3]: “the market is projected to grow from USD 249.83 billion in 2024 to USD 403.29 billion by 2032, exhibiting a CAGR of 6.2 % during the forecast period”.

Aluminium production is thus an energy intensive industry (EII). Energy-intensive industries are a vital part of countries economy and play a critical role in reducing their strategic dependencies. EIIs contribute directly and indirectly, through downstream activities, to a large share of the economy, employment and innovation. They comprise industries such as chemicals, basic metals, non-metallic minerals (ceramics, glass and cement), plastics, paper products, wood and wood products, and food. Part of the EIIs include hard-to-abate activities. These are activities such as cement, glass, steel, chemicals and plastics production, which use fossil resources (coal, gas and oil) as fuel or feedstock. In these segments, greenhouse gas (GHG) emissions are comparatively difficult to reduce using current technologies. But aluminium production is excluded of these segments and has therefore a unique chance to be able to drastically reduce its GHG emissions.

The following Table 1, basing on data compiled in [2], presents, for each step in the aluminium life cycle (excluding usage, the related share of direct energy consumption, the associated GHG emissions and the amount of MWh of electricity per tonne for a conventional process. Aluminium production relies on the electrolytic reduction of alumina in molten cryolite, a process that demands vast amounts of electrical energy.

Table 1. Value chain with direct energy consumption, associated CO₂ emissions and electricity need in MWh.

Process step	Direct energy (GJ)	CO ₂ emission (t/t)	Electricity share in the process energy (%)	Electricity need per tonne (MWh/t)
Bauxite & Alumina	23.3	2.6	7	0.45
Anodes & Smelting	52.4	13.2	98	14.26
Casting & Fabrication	7.1	0.7	33	0.65
Recycling	6.5	0.5	12	0.22

Accordingly, the main process electricity is consumed during the electrolysis process in the smelter. Due to the world average electricity mix being mainly based on coal, this production step accounts for 77 % of the CO₂ emissions associated with the production and recycling of one tonne of aluminium.

Thus, the most efficient measure to decrease the aluminium carbon footprint is to replace carbon intensive electricity by low carbon one in smelters operation. If one compares on this only base a tonne of aluminium produced in 2023 in France (mix 2023 = 32 g CO₂eq/kWh according to RTE [4]) or in China (582 g CO₂eq/kWh according to Statista [5]), the CO₂ content of the electricity needed for the smelting process will account for each tonne of aluminium 0.46 tonne of CO₂ in France and 8.3 tonnes of CO₂ in China. Even if the focus of the industries has been put on energy efficiency in the past and thus reducing the cost and GHG emission, the present rapid calculation shows that moving towards low carbon electricity will be by far more efficient in the carbon footprint reduction.

2.1 Implicit and Explicit Electrical Flexibilities

Electrical flexibility [6] refers to the ability of energy systems, in particular stand-alone or interconnected electrical systems, to adjust energy consumption or generation in response to

changing conditions, such as fluctuations in demand or supply, particularly to maintain grid stability. Flexibility is becoming more important due to the increasing integration of renewable energy sources, which are intermittent by nature (e.g. solar and wind). This flexibility can be categorized into two main types: implicit and explicit.

2.1.1 Implicit Electrical Flexibility

Implicit flexibility (also called demand-side flexibility or procurement price-based flexibility) occurs when end-users adjust their electricity consumption in response to retail market signals, without being directly instructed to do so. This is usually driven by spot price signals that vary depending on the time of day. Implicit flexibility is therefore a behind-the-meter optimization that lowers the energy bill.

2.1.2 Explicit Electrical Flexibility

Explicit flexibility (also called direct control flexibility or contractual flexibility) involves end-users or third parties (like aggregators) providing specific flexibility services to grid operators. This typically involves an agreement where a certain amount of electricity consumption or generation can be directly controlled or adjusted by the utility, grid operator or as an answer to a structured market operated by such, in exchange of financial compensation.

2.1.3 Demand-Response Programs

Flexibility activation can be performed through diverse types of demand-response programs as illustrated in Figure 1. Depending on the local technical and regulatory framework, procurement prices may be more or less dynamic. In a similar way, the level of electricity market liberalization may be more or less deployed so that the explicit flexibility is leveraged to the benefit of the system operator either by bidding on a market or by applying binding technical rules.

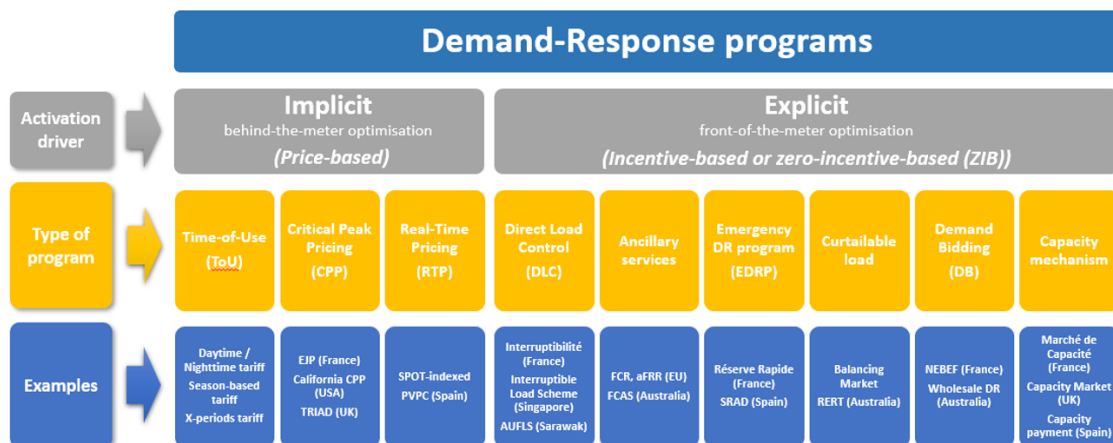


Figure 1. Types of flexibility programs that can be carried out in terms of explicit and implicit flexibility and illustration in different national markets.

2.2 Consumption Flexibility Need

With growing shares of renewable energies in the mixes, grids require increasing flexibility of the consumption.

The activation of flexibilities has an economic impact on the energy bill: indeed, implicit flexibility allows a load modulation as an answer to spot prices so that maximum consumption can be synchronized either with local energy production or with lowest spot prices.

Secondly, the CO₂ content of the consumed MWh depends on the resource that was used to generate the MWh. As a consequence, a real time CO₂ content of the electricity mix can be calculated. For the French mix, the CO₂ content is published in real time by the Transmission System Operator (TSO) – RTE in France [4, 7]. With increasing penetration of renewable energies, the correlation between the spot price and the CO₂ content increases, so that cheap electricity has a low CO₂ content because it is produced either from renewable sources (wind, solar and hydropower) or from nuclear. Thus, alignment of economic and environmental objectives is provided as shown in Figure 2.



Figure 2. RTE market price and CO₂ content of electricity in France on a conventional working day.

On the 28th of August 2024, at 2:00 pm, the CO₂ content of electricity is at its lowest level with 16 g CO₂eq/kWh. At the same time the lowest price of the day is reached with 18.12 EUR/MWh.

As a result, displacing part of the electricity consumption of a flexible process (e.g. steam generation by an electrical boiler coupled with a well sized heat storage) can lead to substantial reductions, both in the electricity bill and in the CO₂ footprint.

Historically, aluminium smelters have maintained steady and consistent energy consumption patterns to ensure process stability and optimize production efficiency. The increased penetration of renewable energy in the electricity mixes is progressively putting pressure on such operating schemes. As a first result, procurement strategies for aluminium producers are evolving in liberalized markets. Indeed, in such markets with growing share of renewables, negative spot prices are encountered more and more often.

Why do negative electricity prices occur? Why would market participants pay to produce electricity instead of simply turning off production? Let's explore the key reasons.

In first line, for certain power plants, such as nuclear or large thermal plants, shutting down and restarting involves significant costs. These facilities often remain operational during brief periods of negative prices, as the expense of switching off outweighs the temporary negative revenue. Similarly, some producers cannot easily reduce their output or shut down.

For example:

- Large hydropower plants may need to keep generating if reservoirs are full and lack a bypass system.
- Run-of-river hydropower plants may lack the capability to stop production.
- Rooftop solar installations are often designed to generate continuously, without responding to market conditions.

This inability is often linked to a lack of incentives for installing mechanisms to reduce or control generation output.

Support mechanisms like feed-in tariffs or net metering can also disconnect producers' revenues from market prices, as well as fixed remuneration contracts. A feed-in tariff guarantees a fixed income per kWh, encouraging maximum output, regardless of market price. Similarly, green certificates add a constant premium to the market price, incentivizing generation even when prices are low or negative.

There are few other reasons why producers may accept to pay in order to get rid of their production and negative prices are not unique to electricity markets. Other commodities, like natural gas and oil, have also experienced negative prices, particularly during periods of oversupply and limited storage options. For example, U.S. natural gas prices turned negative during a heatwave when maintenance work trapped gas supplies.

As a general trend, in the short-term, occurrence of negative prices is likely to increase as solar power installations rise and support schemes have not yet adapted to mitigate the issue. And this is a unique opportunity for flexible electricity consumers. The following figure results from a simulation of the production-consumption balance on the French network as expected in the RTE scenario of 2030.

In the following Figure 3, the projected number of hours in the year with excess energy is exceeding 7 000 while around 1 800 hours correspond to energy deficit. The periods of structural deficit will need to be compensated by demand side management while the excess periods will be an opportunity for flexible consumers, either on the spot market or through stimulation balancing mechanisms.

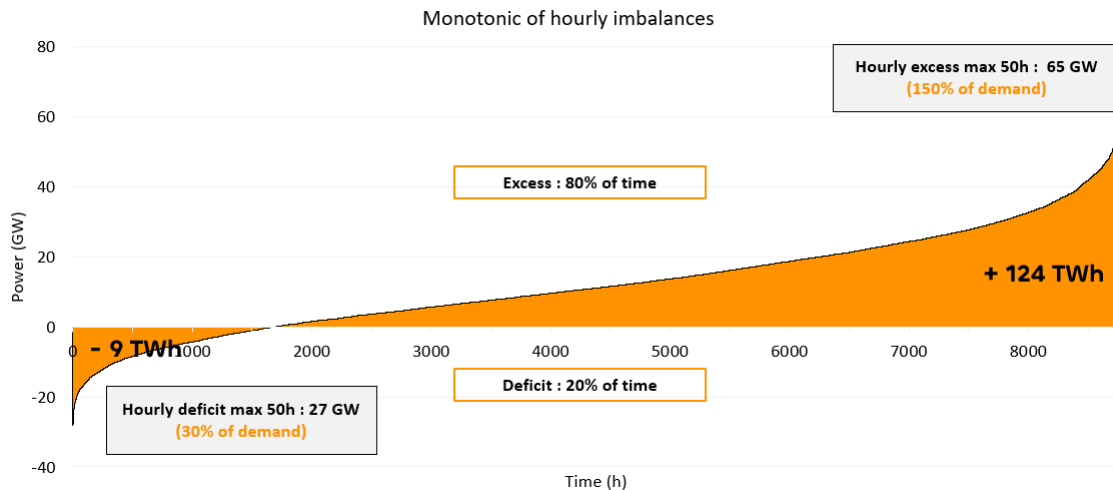


Figure 3. Structural imbalance of the French power system anticipated for 2030 basing on medium RTE energy mix and consumption scenario.

Figure 4 is schematic of the new trend in electricity procurement for EIIs. The fact of becoming flexible allows benefitting of the negative spot prices events: they have more than doubled from 2023 to 2024 in France as can be seen in the left table. Therefore, procurement strategies tend to evolve toward securing only part of the electricity need on the long-term markets with products such as PPAs (power purchase agreement that are bilateral contract between a producer and a consumer) and for the rest of the need, benefitting of low spot prices as much as possible.

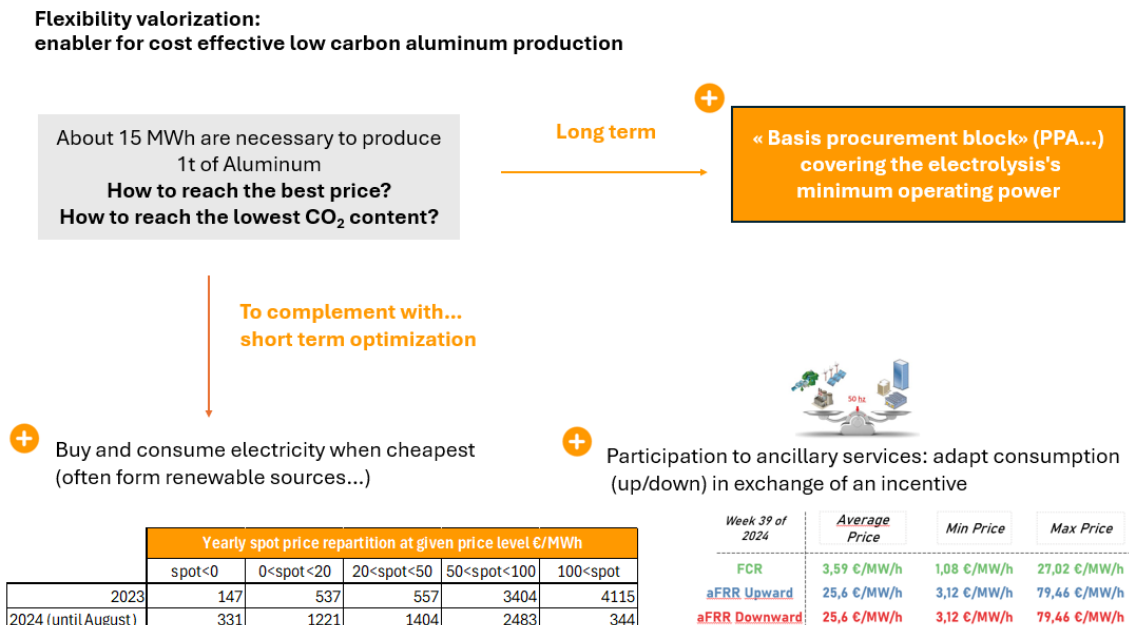


Figure 4. Optimum electricity procurement strategy for an aluminium producer in a liberalized market.

The different customers advantages of flexibility are summarized in Figure 5: They base on maximizing the self-consumption of locally produced energy (e.g. a prosumer is an energy consumer that produces locally part of its energy needs), optimizing the energy expenses by implicit flexibility actions and generating additional revenues by providing grid services.

**FLEXIBILIZE AND OPTIMIZE ENERGY SYSTEMS
BY OPERATING EXISTING AND NEW ASSETS IN THE OPTIMIZED WAY**

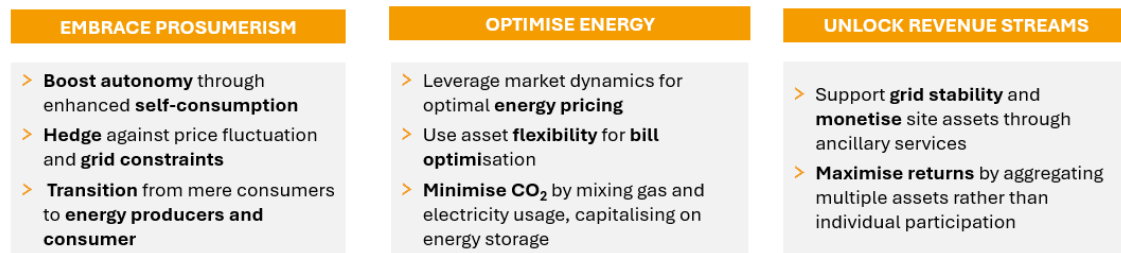


Figure 5. Advantages of flexibility leveraging.

Thus, the benefit of becoming flexible is threefold: economic, environmental and social as the industrial consumer become part of the grid infrastructure of its country and contributes to its stability.

3. Identifying and Increasing Flexibility in the Production Process

The first action undertaken to optimize the energy budget of an industrial production site through flexibility activation lies in the identification of the flexible power potential. This happens through a thorough analysis of the plants load curve and a technical study of the process and surrounding utilities.

Indeed, optimizing the flexibility activation requires a holistic approach at the convergence between technical, economical and industrial constraints. It also requires an in-depth knowledge of the technical rules, regulatory framework and opportunities in the country where the plant is located. An illustration of the different explicit flexibility markets accessible for an electro-intensive industry in France is presented in the following Figure 6.

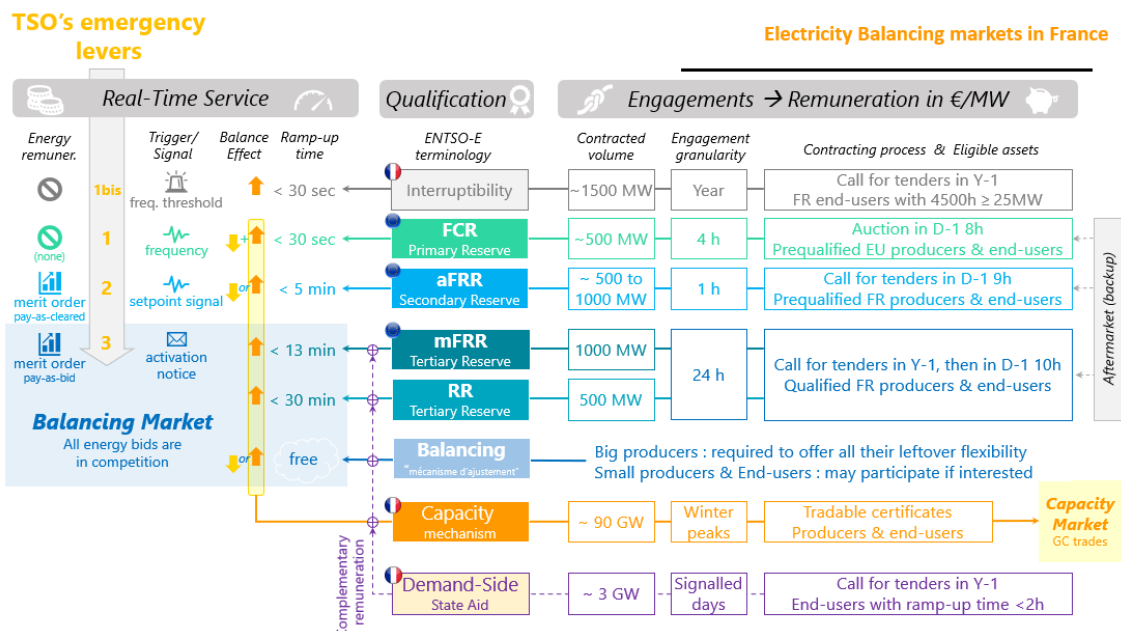


Figure 6. Electricity balancing markets in France: Service, contracted volume, engagement granularity, remuneration and contracting process. (markets with a French flag: mechanisms are specific to France and considered as a stated aid).

The different mechanisms are timely correlated to each other and activated sequentially by the TSO to compensate for imbalances resulting from the non-predicted/non-predictable events on the grid. The sequence of activation of the different reserves that were awarded capacity remuneration on the timestep is shown in Figure 7. In case of power loss (here 1.5 GW) the grid frequency will drop within few seconds. The FCR is activated automatically and will care for frequency containment within the first 30 seconds after event. Then aFRR is activated and will lead to restauration of the grid frequency to its nominal value while FCR is made available for a hypothetical second failure. After less than 10 minutes, manual frequency restauration reserve is activated so that aFRR is made available again.

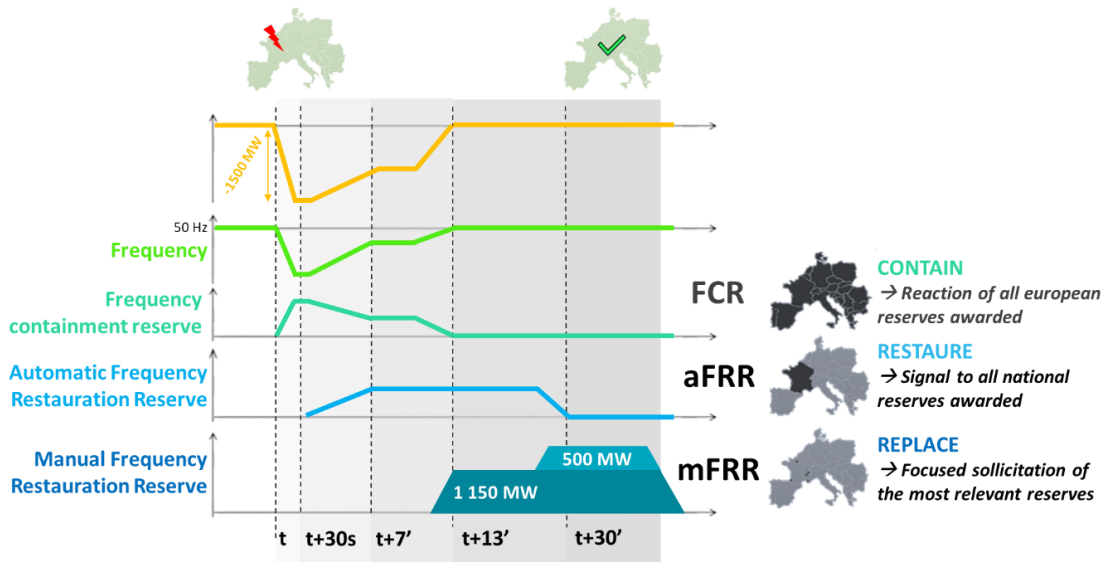


Figure 7. Illustration of a critical event on the French grid (example of a power-plant failure) and how the different awarded reserves are activated to return to the point of supply-demand balance.

In order to capture the flexibility of a process and be able to propose it on at least one of the balancing market mechanisms illustrated in Figure 7, a multistep approach needs to be conducted which necessitates to dive deeper in the process and the surrounding equipment constraints and availability. The different steps consist of (1) the audit of the plant to identify flexibility in the process and the surrounding utilities, (2) a determination of the technical feasibility at best possible CAPEX, (3) an implementation, (4) when needed a certification towards the TSO followed by (5) operations.

Regarding the technical feasibility and implementation, constraints related to the equipment and the process often induce a need in advanced engineering solutions. Examples of Technical requirements for fulfilling the service, related constraints put on the process and assets, and solutions designed and implemented by the aggregator for the industrial customers are presented in Table 2.

The technical adaptations listed here are the ones that emerge from a collaborative work between the industry specialist and the aggregator; they are of course complementary of the different solutions that are for some of them already implemented in the aluminium industry in order to modulate the input power and that were summarized in the paper from Martin Iffert [2] such as:

- Modulating the heat loss from the cell through the top and the side
- Implementing solutions for magnetic compensation (internal or external)
- Deploying energy state adaptive pot control systems
- Upgrading the high-voltage system with transducers or thyristors

Table 2. Technical requirements for fulfilling an ancillary service, related constraints put on the process and assets, and example of implemented solutions for industrial customers.

Technical requirement to fulfil	Constraint	Example of implemented solution
Ramp / Short term signal	Must be adapted to both process and available equipment on site	Use of existing older power electronics to minimise CapEx: patent EP4348821
Power	Minimum power required for participation in the ancillary services	Assets pooling either on site or through the aggregator
Energy	May impact process stability	Energy pricing strategy in bids programming is designed to stay in the acceptable bandwidth
Number of occurrences / modulation	May affect equipment longevity e.g. H ₂ electrolysers undergo “fatigue” of the membranes	Determine with industry specialist what number and amplitude of oscillations are acceptable for a same energy throughput

4. aFRR: Rules for Participation and Certification Process in France

Up to now, in France, automatic frequency restoration reserves were provided by power plants that had the constructive obligation to do so. The remuneration for it was in the order of magnitude of 22 EUR/MWh before becoming an open market. The generic rules for participating in the newly opened aFRR market are presented in Figure 8.

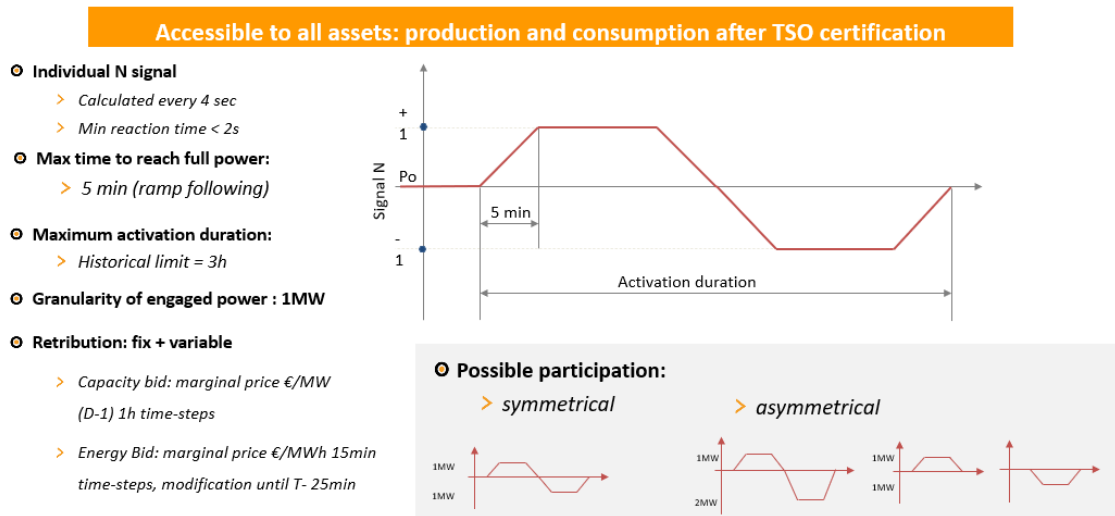


Figure 8. Basic rules for aFRR participation in France (august 2024).

The new rules for aFRR in France (Figure 8) differ only slightly from others in Europe and will progressively be harmonized so as to offer market coupling. They allow participation on limited periods: bidding is performed one day in advance on hourly time steps with intraday reprogramming so that the prices can be resubmitted 25 min before real time. The offers can be asymmetrical (only up, only down or with different prices up and down). The signal N (1, 0 or -1) is actualized every 4 seconds, and the balancing power needs to start ramping within 2 seconds. Full power must be reached within 5 minutes. There is theoretically no maximum activation duration in a single direction but there is no historical recording lasting for more than 3 hours. The retribution for the service consists of a capacity payment in pay-as-cleared and a payment of the activated energy. Assets that were not selected in capacity auction can of course still participate on the D-day with energy bids.

Before being able to place bids, an asset or a pool of assets needs to be certified by the TSO. The certification process will certify the whole communication chain, the control algorithm and the asset itself. A certification process is therefore quite costly and can last from 3 to 6 months depending on the complexity of the pool to certify and on the number of certification requirements the TSO is facing. An example is given in Figure 9 of the tests that are underwent during the certification process, the most impacting one being the “8 hours stress test” in real conditions.

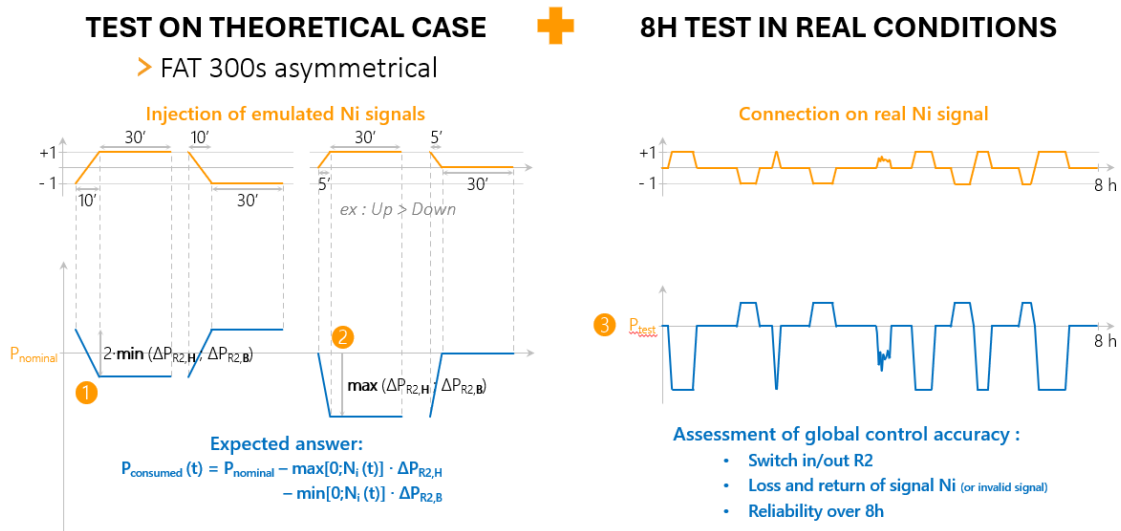


Figure 9. Description of test sequence in aFRR certification process for a consuming asset or pool of assets creating a reserve entity.

5. Advanced Strategies for Optimum Operations

Flexibility degrees offered by the aFRR rules allow asymmetrical bidding so that appropriate bidding algorithms can regenerate the optimal operating conditions for the process. Present on the aFRR energy market right at its opening in November 2023, Energy Pool could observe the two following points during the first year of operating assets on this market:

- Symmetrical offers are preferred by the TSO.
- 2 % of the time i.e. 160 h/year, the offers at the maximum energy price are activated

This knowledge is of utmost importance when designing the bidding algorithms and targeting the best economic value.

Figure 10 illustrates the operation of a Sodium Chlorine electrolyser. In this case, the price algorithm is designed for regulated power containment. As a result, the difference between the actual power consumption (in green) and the forecasted operation (in violet) is kept low.

In such operations, the objective function is of course the maximization of revenue, but constraint function stays with the thermodynamic stability of the process. Innovative solutions can be designed coupling these constraints and come out of the tight collaboration between the asset owner and the aggregator providing market access.

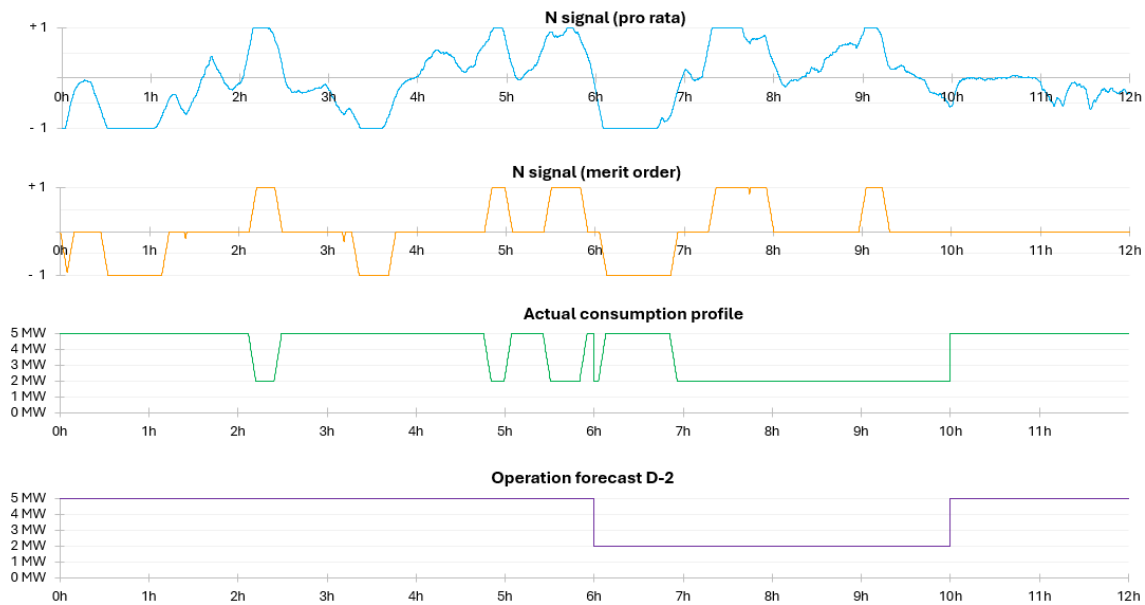


Figure 10. Real operation of a Sodium chloride electrolyser.

6. aFRR in France, Early Opening Prices and Planned Evolution

Since market opening, the energy prices have been lower than expected but the capacity prices much higher. Before market opening, the aFRR service used to be provided because of a regulatory obligation, remuneration was around 22 EUR/MWh and the service had to be symmetrical. This amounted to a value around 193 kEUR per MW available 8 800 hours a year in upward and downward directions.

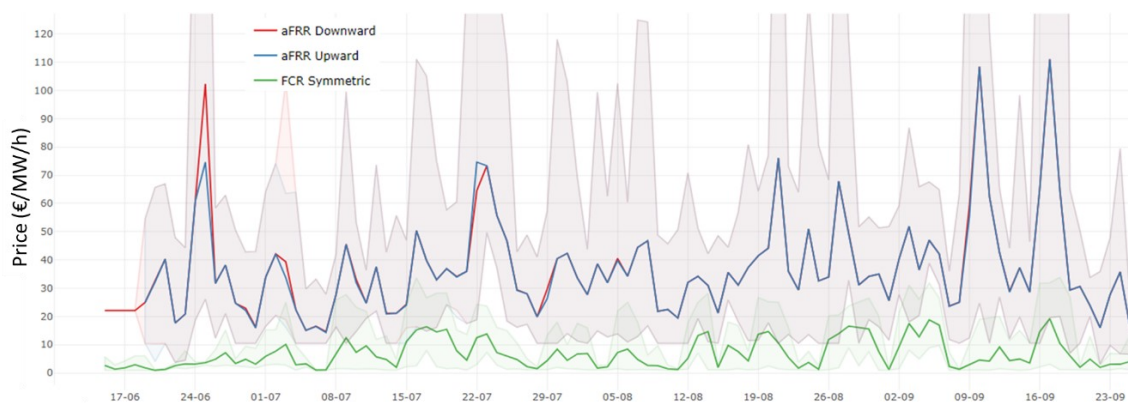


Figure 11. Capacity prices of aFRR and FCR prices on the French market since aFRR opening in June 2024.

Figure 11 shows the historical capacity prices of aFRR up (blue) and down (red) since the capacity aFRR market opened in June 2024. In the last week of September, the average values were respectively 25.6 EUR/MWh for aFRR up, 25.6 EUR/MWh for aFRR down (and 3.59 EUR/MWh for FCR). Averaged and extrapolated on a full year, the historical aFRR values would lead to an income per symmetrical available MW in the range of 700 kEUR and more. On top of this, the balanced energy should be added.

Before market opening, basing on expert data and comparison with other European markets, the value for single direction aFRR was expected in the range of 8 to 10 EUR/MWh, a bit lower than

the historical remuneration of obliged assets. Few conclusions can be drawn from the present price levels:

- the initial remuneration of 22 EUR/MWh did most probably not cover the cost of operating the production assets at 4 % less than their nominal power.
- At the time being, there is a lack of offer on the French market
- Prices tend to be lower during weekends eventually due to the fact that consumption is low while production from conventional power plants is still high.

The aFRR prices are expected to decrease with increasing availability of certified assets on the French grid. Batteries in particular are expected to be technically well suited for aFRR supply. In its reference scenario for 2030 [8], RTE forecasts 6 GW of batteries available on the French transmission system. Indeed, numerous projects (5.8 GW) are presently in the pipe for network connection but up to now only 917 MW are connected as of 1st of July 2024 [9] and larger projects are undergoing delays. Since batteries are expected to base their business model mainly on aFRR and since the required amount of aFRR for RTE is daily comprised between 500 MW and 1 GW [10], there is a risk of overcapacity if all projects become concrete. Nevertheless, in Germany one can observe that despite a larger amount grid scale batteries in operation (7 GW) the aFRR prices are still high, in particular at times in the day where extreme photovoltaic production is available [11]. In France, a price decrease in aFRR is not expected within the next few years.

7. Advanced Strategies for Multimarket Revenue Operations

While the aFRR market is seen in the medium term as the most profitable for assets like electrolysers that can offer dynamic flexibility, on the long-term, flexible electrolysers will be able to operate as “virtual batteries”. If one elaborates on the technical similarity with a battery’s behaviour, the electrolyser’s flexibility will be valorised on diverse revenue streams, either at the same time (SPOT + FCR or SPOT + aFRR) or successively.

In order to optimize such revenue stacking, special control and bidding were developed within Energy Pool. An example is the one of a prosumer’s site in the Netherlands who needs large heat amounts for its operations. The assets present on the site are described in Figure 12.

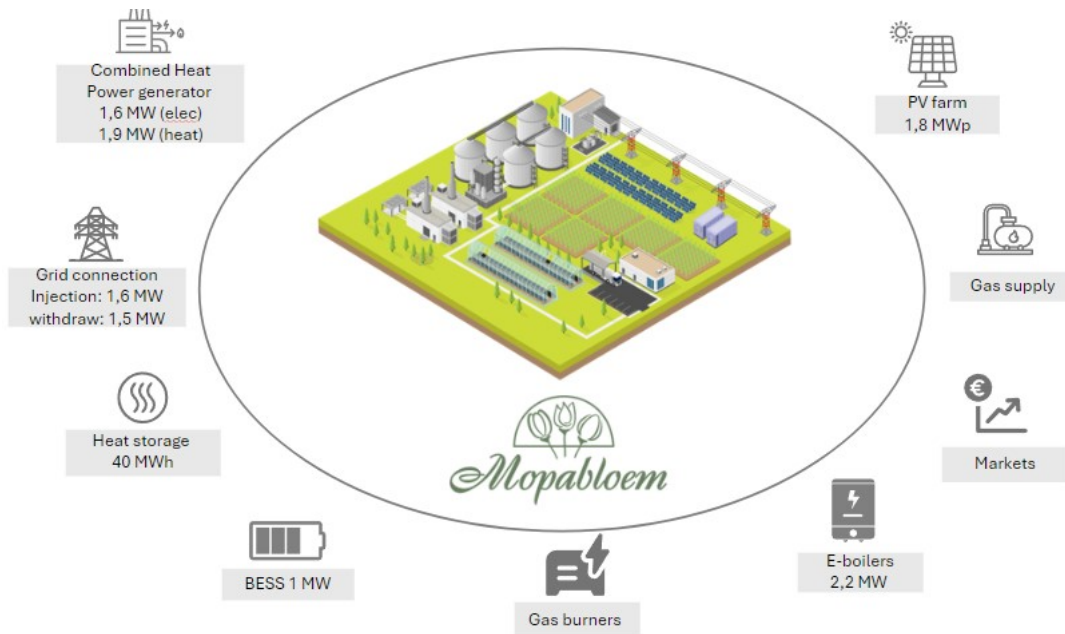


Figure 12. Configuration of site in the Netherland with CHP, gas burner, e-boilers, heat storage and PV production.

Operating the assets of this complex site is performed based on a strategy that maximizes benefits but delivers the heat needed for the production process.

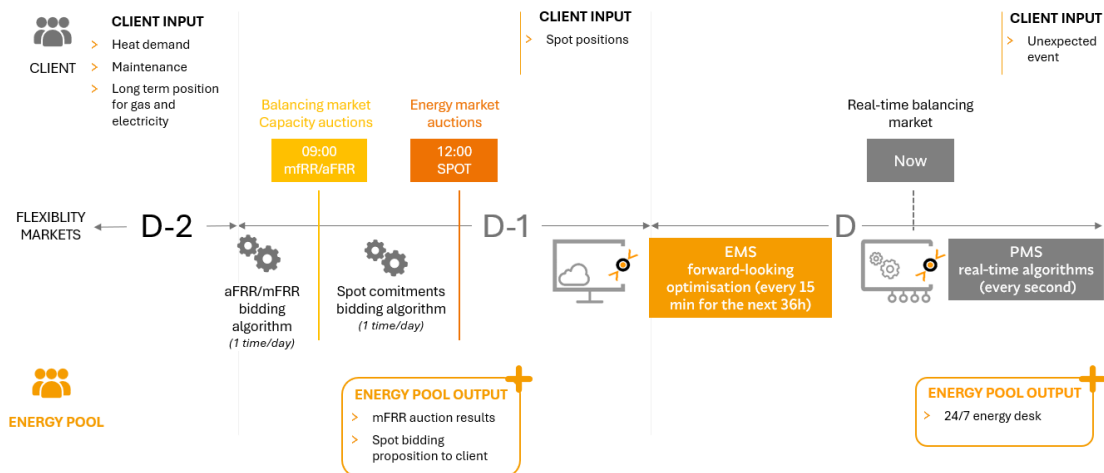


Figure 13. Energy Management System deployed on a site in Netherland form managing self-consumption and maximizing additional revenues on flexibility markets.

For such operations, accurate forecasts of meteorological conditions, heat needs, photovoltaic production and market prices are needed. These forecasts feed the optimisation algorithm that delivers and places the capacity auctions on the balancing markets aFRR and mFRR (manual Frequency Restoration Reserve). From the results of these auctions, spot positions are derived and placed. Then the energy management system is issuing the predicted setpoints of all assets for the next 36 hours with actualisation every 15 minutes. The Power Management System dispatches and actuates the assets to carry out the plan and reacts to any unpredicted event at a timestep of one second.

With such advanced control strategies, both implicit and explicit flexibilities are involved for lowering the global energy bill including gas and electricity and generating additional revenue from ancillary services to the grid.

8. Conclusions

Aluminium production accounts for 4 % of the global electricity demand and 3 % of the global greenhouse gas emissions worldwide. In addition, the need for aluminium is expected to grow and has to grow to provide materials for the energy transition. Therefore, the pressure toward low carbon aluminium is high and should be increasing in the years to come. While energy efficiency improvements were obtained in the last years, energy efficiency alone will not be sufficient to decrease drastically the GHG footprint of aluminium. Aluminium production needs cheap low carbon electricity. And by chance, renewable energies are providing such electricity but on an intermittent basis. Therefore, flexibilization of the aluminium production processes will be necessary both to synchronize consumption with production but also to support grid stability. To maximize their use of green electricity, aluminium production plants must become a kind of virtual batteries, ramping up in times of low or negative spot prices or locally consuming self-generated solar or wind energy. And in the same way as a battery, an aluminium production plant can stack revenues by offering its flexibility to the grid for balancing services. Indeed, with growing penetration of renewables the grids are more constrained and in need of more balancing power. The unique technical characteristics of electrolyzers allows them to participate in the automatic frequency restoration reserve markets that are expected to be highly profitable in the years to come in high renewable energy share geographies. Thus economic, environmental and social impacts are perfectly aligned for aluminium production in such grids.

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