

# Scope of the Thesis “Adapting regulatory and market frameworks to enable the mobilization of power system flexibility during periods of high renewable energy generation”

This document introduces the doctoral research initiated by Clara GIROUD-GERBETANT within the Energy Markets and Sustainable Industries Chair at the LGI laboratory of CentraleSupélec, Université Paris-Saclay, in partnership with RTE.

As part of its legal remit, RTE must always ensure a balance between electricity production and consumption. The Energy Transition is currently causing profound changes in the French electricity system: the electrification of uses and the integration of variable Renewable Energy Sources (vRES) pose new challenges for the operational management of the balance between production and consumption. To continue to ensure the security of the system, the development of power system flexibility will be a major lever for balancing in the future.

Despite consensus on the importance of flexibility for the large-scale integration of renewable energies, the development of current flexibility levers is hampered by several major obstacles, such as: inadequate networks (particularly tariff structures), the complexity of market mechanisms, the economic signals sent, and low consumer engagement, in a context where incentive signals and planning remain limited (CRE, 2023; ADEME, 2025).

In recent years, numerous academic studies have highlighted the shortcomings of European architecture in generating the right investment signals. This research has led to proposals for “hybrid” markets, in which the energy-only market is supplemented by capacity instruments or long-term contracts. However, these various studies have assumed that effective programming of production and flexibility resources would be ensured in the short term (mainly on D-1) by the markets. The massive development of vRES with zero marginal cost and storage facilities calls into question the ability of short-term markets to ensure this planning effectively. Indeed, with recurring periods of zero or even negative prices, how can price coordination effectively ensure this planning while guaranteeing the balance between supply and demand?

## I- Background Information

### **Liberalization of the electricity market**

In 1996, the European Union began liberalizing the electricity market by opening certain activities such as electricity generation, supply, and trading to competition. This step marked the transition from an integrated monopoly system to a competitive market, with the aim of increasing economic efficiency and ultimately reducing costs for consumers, as well as stimulating innovation in this field.

Academic literature from the early 21st century (IEA, 2001; Stoft, 2002; NERA Economic Consulting, 2008) highlights the main benefits for end consumers and the environment of opening the electricity market to competition, while anticipating the main risks and distortions identified. Indeed, while the price signal, based on the marginal cost price system, theoretically makes it possible to integrate the instantaneous scarcity of electricity and constraints on the grid, optimizing the allocation of

resources, it does not necessarily send the right signals to investors. The concept of “missing money” has been quickly identified and highlights the difficulty of short-term market prices in covering producers' fixed costs on a sustainable basis, thus creating a challenge in terms of balancing short-term equilibrium and long-term investments.

To meet this challenge, several complementary long-term mechanisms are being implemented to guarantee security of supply and guide investment (long-term contracts, capacity mechanisms, strategic reserves, etc.). This enables the implementation of active flexibility management, which is becoming crucial to ensuring the balance between supply and demand. The penetration of vRES into the electricity mix will only reinforce this need.

### **Decarbonization targets and the rise of renewable energies**

The Kyoto Protocol, signed in 1997 at COP3, is the first binding international agreement aimed at reducing greenhouse gas (GHG) emissions responsible for climate change. It set an overall reduction target of at least 5% by 2012 compared to 1990 levels for 38 industrialized countries, without defining any real penalty mechanism. Developing countries are not subject to these obligations, thus limiting the effectiveness of the agreement. In 2012, despite overall compliance with the above-mentioned targets, global emissions continued to rise, mainly due to the withdrawal of countries such as the United States and Canada, but also due to the rise of emerging economies such as China and India. The Doha Amendment (2012) established a second commitment period (2013-2020) with a new reduction target set at 18%. Several major emitting countries (the United States, Canada, Japan and Russia) remained outside the agreement. A universal framework involving emerging economies was established only with the adoption of the Paris Agreement at COP21 in 2015. This agreement marks a major turning point in climate governance and highlights the urgent need to transform global energy systems, paving the way for the rise of renewable energies.

In line with international climate agreements, the European Union has successively adopted directives to structure its renewable energy development policy. Since 2009, the EU has set quantified targets in this area:

- 20% renewable energy in final energy consumption by 2020, set in Directive 2009/28/EC – RED I
- 32% renewable energy in final energy consumption by 2030, set in Directive 2018/2001 – RED II
- Target revised to 42.5% by 2030 in Directive 2023/2413 – RED III

In addition, the Clean Energy Package (containing eight legislative texts) was adopted by the EU in 2019 to accelerate the energy transition. These legislative acts aim to decarbonize the energy system, improve energy efficiency, increase the share of renewables, strengthen consumer rights, and adapt electricity markets and networks to new energy realities.

### **Public support and the paradigm of Market Hybridization**

The expansion of RES in France has been facilitated by the implementation of public financial support mechanisms, notably through feed-in tariff (FiT). During the 1990s and 2000s, the dominant strategy involved guaranteed purchase prices to incentivize investment. While this mechanism ensured revenue stability for producers, it frequently imposed a significant burden on public finances. To foster the market integration of renewables, the European Union has increasingly

advocated for feed-in premiums (FiP). Under this framework, producers sell electricity directly at market prices and receive a top-up premium, a method designed to enhance the price-responsiveness of renewable generation.

The increasing penetration of RES into the electricity mix, coupled with these support schemes has precipitated the phenomenon of market hybridization (Roques & Finon, 2017). Due to their near-zero marginal costs, renewable energies exert downward pressure on average annual prices in wholesale markets (a phenomenon known as the merit-order effect) thereby eroding producer revenues and distorting long-term price signals. Consequently, long-term contracts that remunerate capacity and safeguard adequacy of supply are becoming indispensable. As noted by Roques and Finon, the pursuit of an optimal balance between regulatory intervention and market coordination is a structural necessity: a hybrid system appears “inevitable” to reconcile decarbonization target, security of supply and economic efficiency.

With a high share of RES, market prices frequently reach zero or become negative during specific period. The near-zero marginal cost of these sources displaces conventional thermal plants in the merit order (economic precedence). To mitigate this, enhancing and mobilizing flexibility resources is paramount. Thus, Finon and Roques (2017) emphasize that the electricity market must evolve towards a more sophisticated design, where short-term price signals and long-term planning complement one another. This evolution is crucial for a reliable energy transition, particularly as it implies a systemic increase in the requirement for short-term flexibility.

### **Electrical flexibility according to temporal horizons**

Flexibility responds to needs that differ in nature, scale, and timing. As we approach real-time operation, stochastic uncertainties (mainly related to weather) decrease, and flexibility requirements become more precise and specific. Heggarty (2020) quantifies the effective provision of flexibility by these different levers, demonstrating that flexibility can be provided by various technological means (batteries, pumped-hydro storage, demand-side management, power-to-gas, etc.) and at different operational scales depending on the time horizon:

- Structural and regular flexibility accounts for most volume requirements. It is predictable because it is linked to cyclical phenomena (ambient temperature, socio-economic rhythms, diurnal photovoltaic production). Its role is to adapt the load curve so that electricity is consumed when it is most available and decarbonized. It operates across different time horizons:
  - Inter-seasonal: management of production resources to ensure maximum resource availability during winter.
  - Intra-weekly: optimization of storage and shiftable consumption to manage variations between weekdays and weekends.
  - Intra-daily: smoothing daily peaks by shifting consumption or using storage (batteries, pumped storage). This is particularly important for smoothing the daily cycle of residual consumption linked to human activity and the photovoltaic profile (which creates a duck curve, illustrated below). This requirement includes energy shifting and ramp management.

- Dynamic flexibilities are mobilized from a few days to a few hours before real time. They allow for adjustment in production or consumption to adapt to meteorological conditions and to respond to forecast deviations, particularly in wind and solar power production or demand. This includes dispatchable means of production, storage and consumption shift, whether integrated into the markets or via specific offers.

- Balancing flexibilities, activated within RTE's operational window, are used to correct the latest contingencies or deviations (e.g. production contingencies, last-minute weather inaccuracies) via:

- The balancing mechanism (with the future participation of the large-scale renewable energy parks)
- Ancillary services (frequency regulation)

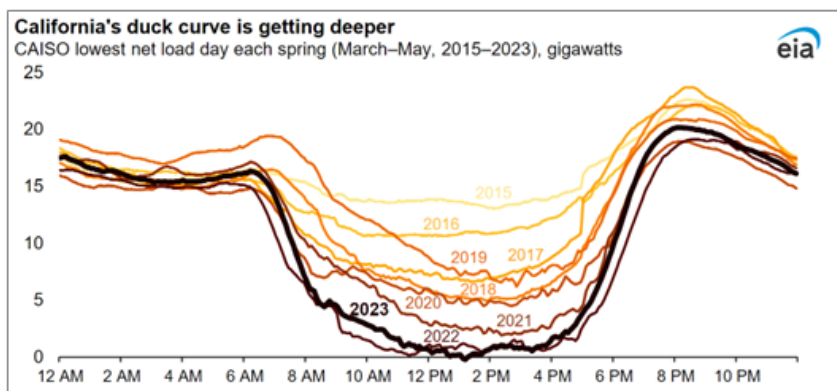
Although crucial to system security, these flexibilities represent a relatively small volume.

- Finally, backup flexibilities are only mobilized in the event of exceptional system stress. They act as a 'safety net' in extreme situations, whether there is a production deficit or surplus. They include:

- Voluntary energy-saving measures (EcoWatt signal),
- Measures to cap consumption or reduce voltage,
- As a last resort, load shedding or forced reduction in production.

The first three categories are used daily as part of normal market operations, through the actions of system stakeholders (producers, suppliers, aggregators, traders, etc.). After the markets close, the TSO (RTE) ensures system balance through contracted flexibility. Backup flexibility, on the other hand, remains exceptional but essential for maintaining system stability in extreme situations.

In addition to conventional production, various flexibility sources are emerging or have been identified in prospective studies: flexibility of renewable energy sources, demand-side flexibility (peak/off-peak tariffs, electrolysis, smart EV charging), and stationary battery storage.



## II- The issue

In an electricity system that is increasingly dependent on variable renewable energies, the question is not only one of having flexibility available, but also of ensuring that it can be mobilized when needed. Waiting until the last minute to act has several limitations: the levers that can be activated become scarce, costs increase, technical requirements become more stringent, and the room for manoeuvres in the event of unforeseen circumstances is reduced. This is why RTE favours a proactive approach: each player must act as soon as they have sufficiently reliable information, considering implementation deadlines. The aim is to mobilize structural and dynamic flexibilities, which are largely predictable, upstream (via the markets) to limit the use of balancing flexibilities, which are more costly and risky. In particular:

- Structural flexibilities make it possible to smooth load curves and adapt consumption to low-carbon production (e.g. solar production).
- Dynamic flexibilities respond to forecast deviations related to weather conditions (temperature, wind).

With the gradual reduction of RTE's operational window, this ability to anticipate becomes central to system security and cost control.

The thesis will therefore focus on the mobilization of these structural and dynamic flexibilities.

Already today, the first difficulties are appearing in operation, with recurring problems of lack of downward balancing flexibility and sometimes delicate management during episodes of negative prices, as follows:

- Financial support mechanisms for RES have been designed to encourage RES to halt production in the event of negative spot prices, but as the situation evolves between D-1 and real time, the shutdowns do not always correspond to the volume required by the system.
- These shutdowns involve very significant ramps, causing frequency instabilities.

They may need to be supplemented by well-localised curtailments to manage network constraints, leading to too many RES being curtailed and other means being used to compensate, due to the limited participation of RES in the adjustment.

These situations are likely to become increasingly frequent and intense. Initial solutions will be implemented (staggered curtailment, mandatory participation of renewable energy farms >10MW in the balancing mechanism), but more structural solutions may be necessary.

Furthermore, difficulties could also be encountered with other types of flexibility. Storage solutions (batteries, demand flexibility based on storage) are particularly difficult to integrate into markets and to determine an optimal schedule. This may lead to considerations regarding:

- The adaptation of market rules and products to facilitate this integration,
- The characterization and rules in the event of tense situations, as the most extreme situations could require more centralized management of these resources.

### III- Objectives of the thesis

The objectives of the thesis will be:

- To identify the different types of flexibility and the conditions for their mobilisation in the French electricity system;
- To characterise the obstacles and inefficiencies in activating flexibility on short-term markets (D-1, intraday), whether related to economic incentives, coordination between actors, technical constraints or current market regulation mechanisms, and the solutions already considered in the literature;
- Study certain inefficiencies in more detail and propose levers for action (market developments, incentive schemes, contractual mechanisms, regulatory obligations) to encourage more proactive mobilisation of flexibility by the various market players.

One research question could be: How can we achieve optimal dispatch of production in a market environment with a proliferation of zero marginal cost and storage resources?

### IV- Thesis schedule

The first part of the thesis (approximately 9 months) will consist of a literature review to identify flexibilities and sources of inefficiencies when they are mobilised. This literature review may lead to the writing of an article.

The structure of the thesis will then depend on the inefficiencies identified as most significant and without solutions in the literature.

Depending on the issues identified, the thesis may be structured around two areas (approximately 9 months each) based on the themes identified (e.g. management of production surpluses, better integration of batteries into daily and intraday markets and processes, etc.).

Each of these areas will give rise to quantitative analyses aimed at quantifying the inefficiencies and the contribution of various possible solutions.

Finally, the last nine months will be devoted to finalising the work and writing the manuscript.

## V- Bibliography

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