aFRR Bidding Strategies

for Home Battery Aggregators

A comparison between Passive Balancing and Automatic Frequency Restoration Reserve Bidding Strategies

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TUDelft

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by

S. J. van Rooij

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An electronic version of this thesis is available at http://repository.tudelft.nl/.

Acknowledgment

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This thesis marks the end of my academic journey and as a Complex Systems Engineering and Management student at TU Delft. Throughout this program, I've gained valuable insights into socio-technical systems, particularly within the energy domain. It has strengthened both my understanding and motivation to pursue a meaningful career at the intersection of energy and systems thinking, with the goal of driving change, enabling the energy transition, and supporting innovation for a more sustainable future.

Sjoerd van Rooij
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Executive Summary

The Dutch electricity system is undergoing a rapid transformation driven by the increasing share of variable renewable energy sources like wind and solar power. This transition, coupled with the electrification of various sectors, is leading to growing imbalances between electricity supply and demand, challenging the stability of the grid. To maintain balance, the Transmission System Operator (TSO), TenneT, relies on balancing services such as the automatic Frequency Restoration Reserve (aFRR). Traditionally provided by conventional power plants, there is a growing need for new flexible resources like Battery Energy Storage Systems (BESS) to participate in these markets.

Currently, the business model for home battery aggregators like Zonneplan is based on "passive balancing," where batteries strategically take out-of-balance positions to profit from imbalance price fluctuations. However, the sudden widespread and simultaneous application of this strategy has led to unintended consequences, including system oscillations and a high frequency of "Regulation State 2" (RS2) quarters, where the system swings between shortage and surplus. This development not only complicates grid management for TenneT but also reduces the profitability of passive balancing for market participants.

In response, TenneT is working to make active participation in the aFRR market more attractive for fast-responding assets like batteries. This research addresses the critical question of whether a shift from passive balancing to active aFRR participation is financially viable for aggregators of home batteries, using Zonneplan as a case study.

This thesis compares the performance of Zonneplan's passive balancing strategy with three simulated aFRR bidding strategies. The research is guided by the following main research question: **How does the performance of aFRR bidding strategies compare to Zonneplan's currently used passive balancing strategy?**

To answer this, the study is structured around three sub-questions:

1. How does the currently used passive balancing strategy of Zonneplan work and how does it perform under the growing frequency of Regulation State 2 ISPs?
2. What are the current trends in the aFRR bidding ladder, prices, and volumes?
3. What are possible bidding strategies for Zonneplan to participate in the Dutch aFRR market and how do they perform?

To answer these research questions, the study applies a mixed-methods approach combining qualitative case analysis, quantitative data analysis, and simulation modeling. Zonneplan's passive balancing strategy was examined through internal documentation and discussions with employees. A backcast of the period January 2024–March 2025 was used to analyze the passive balancing strategy performance using Python, while considering Ex-Post trading and both internal and external portfolio advantages. The aFRR market analysis drew on publicly available TenneT datasets to identify trends in prices, volumes, and bidding ladder. Finally, three aFRR bidding strategies were simulated using a custom-built Python model that replicates bidding, activation, and financial settlement processes at one-minute resolution, enabling a robust comparison with Zonneplan's passive balancing strategy. The model incorporates real-world constraints such as bid timing and state-of-charge limitations.

The analysis of Zonneplan's passive balancing backcast data from January 2024 to March 2025 reveals that while the strategy initially showed growing revenue, its revenue has been declining since

August 2024. This is mainly due to increasing charging costs and partly due to the increased frequency of RS2, which, despite price risk mitigation through Ex-Post trading and Portfolio advantages, limits revenue opportunities.

The aFRR market analysis identifies key trends, including the impact of the European PICASSO platform, which has led to higher activation volumes. While extreme price peaks for upward regulation have become less frequent, average prices remain attractive. A clear daily pattern in aFRR prices, often correlated with Day-Ahead market prices, presents opportunities for dynamic bidding. Three aFRR bidding strategies were simulated: a constant bid strategy, a Day-Ahead price-based strategy, and an intraday price-based strategy. The Day-Ahead price-based strategy (Bid Strategy 2) yielded the highest net revenue, consistently outperforming the others.

The final comparison shows that the simulated aFRR bid strategy (Bid Strategy 2) consistently generates higher net revenue than the passive balancing strategy throughout the entire analysis period. The aFRR strategy achieves higher activation volumes and benefits from being able to capture revenue during RS2 periods, where passive balancing is ineffective. Furthermore, aFRR participation aligns directly with the TSO's need for system stability, offering a more robust and system-supportive business model.

The discussion highlights key limitations of this research, including limited data availability on passive balancing, simplifications in the bidding simulations, and the rapidly evolving nature of the aFRR market. It also outlines the main implications for the broader context and key stakeholders. For home battery aggregators, the findings demonstrate a clear financial incentive to transition from passive balancing to active aFRR participation, offering not only more stable and higher revenues but also enabling batteries to contribute more effectively to grid stability. For TenneT, it is encouraging that there is a clear financial incentive for aggregators to shift from passive balancing to active aFRR participation. This shift is expected to reduce the frequency oscillations that are currently amplified by uncoordinated passive responses, while enabling batteries to actively support grid stability by following TenneT's aFRR setpoints, effectively using their fast response capabilities to prevent oscillations rather than cause them. Finally, for home battery owners, the study suggests that while passive balancing revenues are declining, participating in aFRR through aggregators can maintain a reasonable payback period.

The research concludes with several suggestions for future work. Future studies should examine how an aFRR-focused strategy can be integrated into broader multi-market value stacking approaches, including intraday arbitrage and selective passive balancing, to reduce revenue volatility and improve overall profitability. More detailed econometric and scenario-based analyses are also needed to better understand aFRR market dynamics, especially in light of regulatory changes and increasing cross-border integration via PICASSO. As battery participation grows, future research should explore potential market saturation effects and their impact on price levels, activation frequency, and aggregator returns. Lastly, the gradual phase-out of gas-fired power plants from balancing markets introduces new uncertainties, warranting investigation into how this shift could affect price volatility, scarcity pricing, and the strategic positioning of new flexible assets like batteries.

Nomenclature

Abbreviation	Description
aFRR	Automatic Frequency Restoration Reserve
BESS	Battery Energy Storage System
BRP	Balancing Responsible Party
BSP	Balancing Service Provider
CMOL	Common Merit Order List
DAM	Day-Ahead Market
DER	Distributed Energy Resource
DLB	Dynamic Load Balancing
DoD	Depth of Discharge
DSO	Distribution System Operator
EBGL	Electricity Balancing Guideline
FCR	Frequency Containment Reserve
FRCE	Frequency Restoration Control Error
IDM	Intraday market
IGCC	International Grid Control Cooperation
ISP	Imbalance Settlement Period
LFC	Load Frequency Control
MIP	Mixed-Integer Programming
mFRR	Manual Frequency Restoration Reserve
MW/MWh	Megawatt / Megawatt-hour
PA	Portfolio Advantage
PICASSO	Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
PV	Photovoltaic
RS1	Regulation State 1
RS2	Regulation State 2
RS-1	Regulation State -1
SIDC	Single Intraday Coupling
SoC	State of Charge
TSO	Transmission System Operator

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1 Introduction

This chapter introduces the research topic, provides the context and outlines the main research problem. It also presents Zonneplan's vision, identifies knowledge gaps and explains the research approach. Finally, it describes how the topic relates to the COSEM master program and gives an overview of the thesis structure.

1.1 Context and challenges

The increasing share of renewable electricity production, primarily from wind and solar, is rapidly transforming the Dutch electricity system. Between 2020 and 2025, the installed capacity of wind and solar power in the Netherlands grew by 119%, with these sources now accounting for approximately 62% of total installed capacity [1]. While this transition towards renewable resources is essential for a sustainable energy future, it also introduces significant variability and uncertainty in electricity supply [2]. Less predictable electricity supply makes it more difficult to ensure that supply and demand meet in real time, which is necessary to maintain grid stability. Even with the continuously improving forecasting methods that help to reduce deviations from day-ahead positions, some forecast error will inevitably persist due to the inherent unpredictability of weather patterns. At the same time as we are switching to these intermittent energy resources, the supply and demand of electricity are also growing rapidly because of the current electrification across all sectors [2]. Thus, because of a growing share of renewables and a rapid increase in supply and demand of electricity, the absolute imbalance volumes that must be corrected in real-time is expected to grow [3].

Increased trading activity on the intraday markets confirms the growing need for the market to adjust their position before real-time [4]. If the market fails to match supply and demand in real-time, the Transmission System Operator (TSO) must step in to maintain the system balance on a quarter-hourly bases. In the Netherlands, TenneT is the TSO who uses a combination of Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFRR), and manual Frequency Restoration Reserve (mFRR) to manage the grid in real-time [3]. Traditionally, these balancing services were provided mainly by coal and gas-fired power plants [5]. However, this is changing quickly as coal-fired power plants are decommissioned and gas-fired power plants viability is expected to be at risk around 2030 [6]. The role of new types of flexible resources is therefore expected to become increasingly important, which include large-scale Battery Energy Storage Systems (BESS), demand response, and aggregated Distributed Energy Resources (DERs) such as home batteries, electric vehicles, and solar panels [7], [8]. Among these, TenneT [9] sees large-scale BESS and home batteries as especially important for providing future flexibility services.

The current growth in home batteries sales however is fueled by the increase in marketing efforts, the upcoming abolition of net metering and the introduction of the feed-in fine [10]. Consumers have the expectation that batteries will become an interesting investment to increase the usage of their own PV installation. Business models based on day-ahead arbitrage or increasing PV self-consumption are however not yet profitable [10]. The only profitable and current most widely adopted business model is based on passive balancing, where batteries take a strategic off-balance position based on the imbalance price. In many cases, passive balancing helps to keep the system in balance. However, the unexpected rapid deployment of this strategy by home battery operators and other types of flexible assets now also seems to lead to a new problem.

While as many market participants react simultaneously and in the same direction, the system can swing from shortage to surplus, or vice versa, within a single Imbalance Settlement Period (ISP). The market design has not adapted quickly enough to accommodate to these rapid passive responses. The result is frequent overshooting, where participants collectively worsen imbalances instead of resolving them. In November 2024 TenneT announced that driven by this development, they are experiencing large and rapid oscillations in the national system imbalance and a high frequency in Regulation State 2 (RS2) Imbalance Settlement Periods (ISPs) [11]. For TenneT, these rapid and large oscillations in system imbalance form the main problem as they complicate the task of maintaining grid stability and meeting EU-imposed quality standards for the continental European network [12]. For operators of flexible assets deploying passive balancing strategies, the increase in RS2 is the main problem, as it directly reduces the profitability of passive balancing and increases risk. Being out of balance always costs money if RS2 applies.

In response the observed problem, TenneT temporarily increased the publication delay of the balance delta from three to five minutes to dampen real-time reactions [11]. This however didn't have the anticipated result and TenneT took an additional short-term measure by to tuning the Load Frequency controller (LFC) controller, which activates aFRR bids, to be able to react quicker to the rapid market responses [12].

To maintain long-term grid stability, TenneT aims to make aFRR participation more accessible and attractive for BESS with fast response capabilities. This is being pursued by lowering entry barriers and developing a faster-responding aFRR product that can better manage system fluctuations. For operators of fast-responding flexible assets, such as aggregators of home batteries, to shift from passive balancing strategies to active participation in aFRR, there must be sufficient financial incentive to do so.

Therefore, this research aims to compare the revenue potential of home battery systems operating under a passive balancing strategy with that of participation in the aFRR market, based on recent historical data. The study includes a case analysis of Zonneplan, an aggregator of home batteries, with whom collaboration was established for this research. Zonneplan's vision is highlighted in section 1.2. The study focuses on how their passive balancing strategy has performed in light of the increasing frequency of Regulation State 2. Several aFRR bidding strategies for batteries are tested to estimate their revenue potential, which is then compared to the performance of Zonneplan's current approach. This research contributes to a better understanding of the differences between both strategies under evolving market conditions and provides an indication of whether transitioning to aFRR is financially attractive for battery operators.

1.2 Zonneplan Flex Vision

Zonneplan's overarching mission is to build a "greener, fairer, and smarter energy network by and for everyone." Zonneplan offers solar panels, EV chargers, home batteries, and dynamic energy contracts. The Flex team is responsible for the intelligent control of these products and has the following vision:

Flex Vision:
"Sustainable energy is extremely cheap but highly variable. Through Flex, we provide a fully managed energy household, allowing people to benefit from the energy transition without any hassle. We offer a comprehensive high-tech solution for managing household energy during the energy transition through managed services. This enables our customers to get the most out of the energy transition without needing to worry about it themselves.

We achieve this in two ways: first, by delivering a suite of controllable products such as home batteries, EV chargers, and solar panels, which we can intelligently manage remotely. Second, we use an intelligent optimizer that creates synergies between energy markets and our controllable assets. This allows us to extract the maximum value from Flex assets."

This research focuses on the intelligent control of home batteries. Zonneplan aims to maximize financial returns for its customers while also contributing effectively to the overall energy system. It is therefore important for Zonneplan to understand the impact of its passive balancing strategy on system. Additionally, Zonneplan is continuously exploring new revenue streams to make its business model less dependent on a single source and to generate more stable, sustainable revenue. If Zonneplan can support the system more effectively by participating in the aFRR market, while also generating more consistent revenue, this would be a highly valuable development. Recently, Zonneplan took an important step by starting to trade home batteries on the intraday market. In the future, this may be expanded to include aFRR, as well as GoPacs and local flexibility markets.

This research presents Zonneplan's passive balancing strategy and analyzes backcasted performance, comparing it to potential participation in the aFRR market.

1.3 Literature review and academic knowledge gap

A literature review was conducted to identify the academic knowledge gap concerning the increase of passive balancing and aFRR bidding strategies for BESS aggregators in the Dutch electricity markets. A structured literature selection process, detailed in Appendix A, was used to find the most relevant research. The search was split into two parts: one focused on aggregators and flexibility service providers, and another specifically targeting the aFRR market. The rationale behind the first string was to concentrate on the actors deploying passive balancing strategies, given that a direct search for "passive balancing" yielded limited results. The term "flexibility service provider" was also employed because both passive balancing and aFRR bidding strategies are not exclusively aggregator-specific and can also be implemented by large-scale battery operators.

Passive balancing
The search revealed only two studies explicitly modeling passive balancing strategies for BESS. One study [13] developed a stochastic model predictive control (MPC) framework for a BESS operating with strategic out-of-balance positions, using a bi-level optimization that captured how BESS actions influenced imbalance prices. Tested on the Belgian market with data from December 2020 and January 2021, this model showed that implicit balancing could achieve much higher profits than day-ahead trading, even under perfect foresight. However, it was tailored to Belgium's single imbalance price system and did not account for the recent rise in passive balancing by BESS aggregators since 2024. It also highlighted that increased market saturation could reverse the imbalance direction

Another study [14] examined passive imbalance trading in the Netherlands, modeling aggregated small-scale BESS portfolios participating in the day-ahead and imbalance markets using 2021 data. It found that passive balancing consistently outperformed day-ahead arbitrage on revenues. Still, under 2021 price levels, passive balancing alone was not profitable for household-scale systems. It concluded that higher volatility expected by 2030 could double imbalance revenues, potentially making passive balancing viable, and recommended that aggregators with portfolios over 1 MW explore entering reserve markets such as aFRR.

These studies show that while passive balancing can outperform day-ahead arbitrage on a revenue basis, profitability depends heavily on market volatility, regulation, and battery scale. Neither study considered the recent increase in frequency oscillations or the higher occurrence of Regulation State 2, which are now beginning to impact passive balancing revenues. Importantly, neither compared passive balancing directly with aFRR bidding.

aFRR bidding strategies for BESS
In contrast, multiple studies explore aFRR bidding strategies for BESS. One study [15] investigated optimal bidding in the German/Austrian aFRR market using 2019 data, developing models that optimized capacity and energy bids while explicitly incorporating degradation. It concluded that

participation was not profitable under 2019 costs but could become viable by 2025 through cost reductions and pooling.

Another study [16] focused on a wind-BESS portfolio in Germany with 2022 data, using a three-stage stochastic model with Conditional value at risk (CvaR) to jointly optimize day-ahead and aFRR participation. It showed increased revenues and reduced imbalance penalties, with aFRR adding significant income. Furthermore, [17] examined BESS in Belgium participating in day-ahead and aFRR markets with joint chance constraints to manage uncertain activations, using 2022 data, achieving over 17% higher profits compared to simpler approaches.

Other research [18] analyzed aggregators of BESS in France participating in FCR, aFRR, mFRR, and replacement reserves, demonstrating through a MILP framework that this strategy outperformed heuristic methods and scaled well to large portfolios. Additionally, [19] using synthetic European scenarios showed that stacking wholesale, reserve, and local flexibility markets could lead to super linear gains. Finally, [20] found that by 2030, higher shares of renewables in Germany would increase day-ahead market attractiveness, but combined strategies involving aFRR would remain essential.

Knowledge gap
These studies provide extensive insight into BESS profitability from aFRR and multi-market strategies across various European systems, mostly using data from 2019 to 2022. However, none directly compare explicit aFRR participation to passive balancing or explore how to jointly optimize these approaches under the Dutch market's specific pricing system and evolving dynamics. This leaves a clear gap. TenneT is currently struggling with large and rapid oscillations in net frequency. A growth in the frequency of RS2 is a consequence of this, putting additional pressure on passive balancing revenues. At the same time, TenneT is actively encouraging BESS participation in aFRR. This underlines the need to understand the trade-offs and performance differences between these strategies in the current Dutch context.

1.4 Societal relevance

The rapid adoption of home batteries is increasingly driven by the emergence of attractive business models offered by aggregators, such as Zonneplan, based on passive balancing. In this approach, aggregated flexibility from thousands of residential batteries is used to respond to the real-time imbalance price, generating financial returns for households without requiring any active involvement. This value proposition has significantly lowered the barrier to entry and is making home batteries a more accessible and financially appealing investment.

However, as households increasingly invest in batteries based on these revenue models, they also become dependent on aggregators for the financial performance of their systems. It is therefore in their interest that the underlying business model remains profitable in the long term. A stable and future-proof revenue framework is essential to ensure that users can recover their investment and achieve the expected returns.

Beyond individual incentives, the effective deployment of home batteries also supports wider societal goals. Smart use of distributed storage helps to stabilize the electricity grid, reduce peak loads, and relieve congestion. This contributes to delaying or avoiding costly grid reinforcements and enables the connection of new homes and businesses. Aligning individual economic incentives with system-level needs makes home batteries a valuable asset in the transition to a flexible, reliable, and sustainable energy system.

Aggregators have the potential to offer highly controllable and distributed flexibility into the aFRR market, which can support system balancing while also opening new and more stable revenue streams.

1.5 Research questions

The Main Research Question is of this thesis is:

How does the performance of aFRR bidding strategies compare to Zonneplan's currently used passive balancing strategy?

To answer this question, the study addresses the following sub-questions (SQ):

SQ1: How does the currently used passive balancing strategy of Zonneplan work and how does it perform under the growing frequency of Regulation State 2 ISPs?

- Objective: To comprehensively describe Zonneplan's passive balancing strategy and evaluate its historical performance, particularly under evolving market conditions characterized by increased RS2 occurrences.
- Method: Qualitative case study and quantitative data analysis.
- SQ1 is answered in Chapter 4.

SQ2: What are the current trends in the aFRR bidding ladder, prices and volumes?

- Objective: To analyze historical aFRR market data to identify key trends, understand market behavior, and provide a contextual basis for evaluating aFRR bidding strategies.
- Method: Quantitative data analysis.
- SQ2 is answered in Chapter 5.

SQ3: What are possible bidding strategies for Zonneplan to participate in the Dutch aFRR market and how do they perform?

- Objective: To develop and simulate various aFRR bidding strategies to estimate their financial viability and understand their operational characteristics for aggregated home battery systems.
- Method: Simulation modelling and data analysis.
- SQ3 is answered in Chapter 6.

1.6 Link with CoSEM

The MSc program in Complex Systems Engineering and Management (CoSEM) focuses on analyzing and designing interventions in complex socio-technical systems. This thesis aligns with its core focus, since the Dutch electricity system is a prime example of such a system. It involves the interaction of technical infrastructure, market mechanisms, regulatory frameworks, and diverse actors including consumers, aggregators, and system operators. The challenges arising from increasing renewable generation, growing imbalances, and evolving market dynamics highlight the complexity of coordinating technical and economic decision-making across system levels.

From a systems engineering perspective, this research investigates how aggregators can effectively contribute to balancing the system through participation in the aFRR market. Doing so requires understanding the technical capabilities of flexible resources, the behavior of market actors under current price incentives and the functioning of the balancing market. These aspects are closely connected, making the problem both technical and organizational, which fits well within the CoSEM perspective.

1.7 Thesis outline

This thesis is structured to systematically address the research questions and provide a comprehensive analysis of aggregated home batteries deploying passive balancing and aFRR bidding strategies:

- **Chapter 1:** Introduction provides the context, problem statement, research questions, and outlines the thesis structure.
- **Chapter 2**: Background offers essential foundational information on the Dutch and European electricity markets and balancing systems.
- **Chapter 3:** Methodology details the approaches employed for passive balancing analysis, aFRR market analysis, and aFRR bid simulations.
- **Chapter 4:** Passive Balancing Analysis presents the in-depth analysis of Zonneplan's passive balancing strategy and its historical performance.
- **Chapter 5:** aFRR Market Analysis provides a detailed examination of the Dutch aFRR market dynamics and trends.
- **Chapter 6:** aFRR Bid Simulation Results presents the outcomes of the aFRR bid simulations including a sensitivity analysis and a comparative analysis with passive balancing.
- **Chapter 7**: Discusses the comparative analysis, the limitations, practical and broader implications and contribution to literature of this thesis.
- **Chapter 8**: In the conclusion, the answers to the research questions are presented. It also suggests what future research could investigate.
- **Appendices** provide supplementary data, literature review tables, and additional Figures to support the main narrative.

2 Background

This chapter provides essential background information on the Dutch and European electricity and balancing markets. It covers the overall system structure, introduces the main market actors, and explains the functioning of the wholesale electricity markets, including the Ex-Post Market. Additionally, it outlines the various balancing products and processes, with special attention given to the PICASSO platform.

2.1 Electricity system

The electricity system is a complex network designed to ensure the continuous flow of power from generation to consumption while maintaining grid stability. Figure 1 from [21] illustrates the fundamental components, actors and interactions of the Dutch liberalized electricity market, split into the institutional and physical layer.

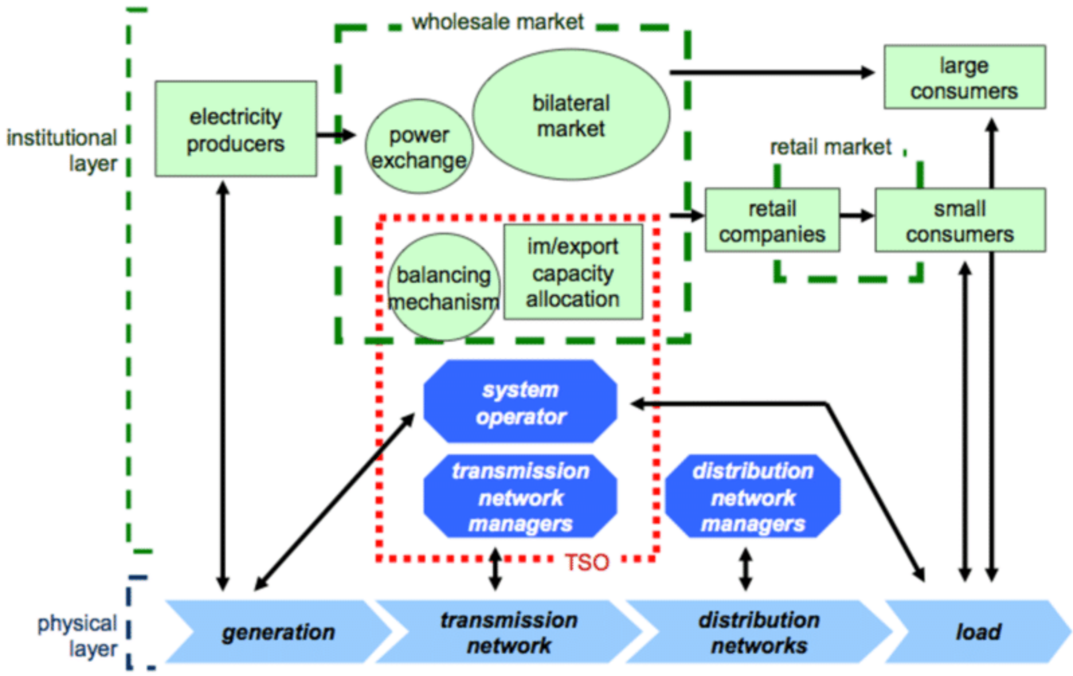


Figure 1: The Dutch liberalized electricity system split into the institutional and physical layer [21].

2.2 European electricity market design

Although this research focuses on the Dutch electricity market as described in Figure 1, its integration with the broader European market must be acknowledged. In recent years, significant efforts have been made to adapt European electricity markets to support the energy transition. Several key legislative developments aim to create a more flexible and integrated system capable of accommodating higher shares of renewable energy [22].

The Renewable Energy Directive (EU) 2018/2001, amended by Directive (EU) 2023/2413, promotes the use of renewable energy and highlights the importance of system flexibility through measures such as demand response, storage, and dispatchable generation.

The Directive on Common Rules for the Internal Market for Electricity (EU) 2019/944 and the Regulation on the Internal Market for Electricity (EU) 2019/943 place consumers at the center of the energy transition. They support active consumer participation, strengthen consumer protection, and enable market-based flexibility, contributing to grid stability and economic growth.[22]
The Electricity Balancing Guideline (EBGL), Regulation (EU) 2017/2195, provides the legal framework for integrating balancing markets across Europe. Its main goals are to increase competition, enable cross-border exchange of balancing services, and improve efficiency and security of supply [23].

PICASSO (Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation) was created in response to Article 21 of the EBGL, which requires a common European platform for exchanging aFRR balancing energy [24]. Because the implementation of PICASSO has a major impact on the Dutch aFRR market it will be discussed in more detail in Section 2.1.5.

2.3 Market roles

TenneT [25] categorizes the roles in the electricity system into the physical and the administrative domain. A third domain, the market domain, encompasses the platforms that facilitate electricity transactions of which a subpart, the wholesale market, is described in the section 2.4.

Physical Domain
The physical domain includes roles directly related to electricity generation, transport, consumption, and grid security. Key players here are electricity producers and consumers, Transmission System Operators (TSOs), and Distribution System Operators (DSOs).

TenneT, as the Dutch TSO, is responsible for the construction, maintenance, and expansion of the high-voltage electricity grid. It ensures the continuous balance between electricity supply and demand by activating balancing products like aFRR. This responsibility makes TenneT central to this research, which focuses on aFRR.

Electricity producers include large plants (e.g., gas-fired) and small installations (e.g., residential solar panels). Due to the growing share of weather-dependent renewables (wind and solar), the grid faces increasing imbalance volumes. These variable sources can also offer flexibility by curtailing production, contributing to balancing markets.

Consumers are transitioning into prosumers, both consuming and generating electricity. Prosumers and small-scale producers are increasingly engaging with aggregators to participate in electricity markets.

Administrative Domain
This domain includes actors that manage relationships between end-users and market or grid operators, handling forecasting, measurement, and billing. The main actors relevant to this study include:

- **Balance Responsible Parties** (BRPs) are responsible for forecasting and balancing the production and consumption within their portfolio for each 15-minute Imbalance Settlement Period (ISP). Deviations are financially settled with TenneT via the imbalance price.

- **Balancing Service Providers** (BSPs) offer balancing capacity and energy to TenneT to maintain system balance. They must register to offer the balancing products FCR, aFRR, and mFRR.
- **Electricity suppliers** buy electricity from wholesale markets and sell it to end-users, managing retail contracts and billing.
- **Aggregators** bundle flexibility from small-scale energy producers and consumers to participate in electricity markets. They aggregate assets such as residential PV systems, electric vehicle (EV) charging stations, and home batteries within their customer portfolio.

Table 1: Electricity system market roles by domain [25]

Market role	Description
Physical domain	
Electricity producer	Produces electricity.
Consumer	Consumes electricity.
Transmission system operator (TSO)	Operates the high-voltage grid and manages the system balance.
Distribution system operator (DSO)	Operates the medium and low-voltage grids.
Administrative domain	
Electricity Suppliers	Buy and sell electricity.
Balancing Responsible Party (BRP)	Required to transmit forecasts of off-take and feed-in through allocation points of its portfolio to TSO. Financially responsible for the balance of their portfolio's off-take and feed-in.
Balancing Service Provider (BSP)	Provides balancing energy and/or capacity to TSO.
Congestion management Services Provider (CSP)	Provides congestion management services to TSO or DSO.
Aggregator	Bundles flexibility and assets from small consumers and producers to participate in electricity markets and minimize consumer electricity costs.

2.4 Wholesale markets

Electricity in the Netherlands is traded across three main types of markets: wholesale, balancing, and congestion markets. The wholesale market consists out of the forward/ futures market, Day-Ahead Market (DAM), Intraday Market (IDM) and Ex-Post Market and can be placed on a timeline ranging from before delivery till day after delivery as described in *Table* 2.

Table 2: Wholesale markets characteristics

Market	Forward and futures market	Day-ahead market	Intraday market	Ex-Post market
Timeline	**Years to days before delivery**	**Day before delivery**	**Day of delivery**	**Between delivery and next day**
Market type	Exchange (futures), OTC (forwards)	Blind auction	Bilateral transactions, Blind auction	Bilateral transactions
Platform	ECE Endex and EEX (futures)	EPEX SPOT and NordPool Spot	EPEX SPOT, Etpa and NordPool spot	EPEX SPOT, Etpa
Time units	A year, quarter, month, week, day	An hour (also quarter hour from Sep-2025 onwards)	An hour, half hour, quarter hour	Quarter hour

Forward and Futures Market

The forward and futures markets enable long-term procurement and price hedging. Futures are standardized and traded on exchanges like ICE Endex, while forward contract such as Power Purchase Agreements (PPAs) are typically bilateral and more flexible. These long-term markets are also accessible to parties that have no physical connection to the grid, which allows for broader participation.

Day-Ahead Market

The Day-Ahead Market (DAM) is the main reference point for electricity prices in Europe. It is organized one day before physical delivery and determines a single market clearing price per hour for each bidding zone. The DAM operates on the principle of marginal pricing, where generators submit bids based on their marginal costs. This ensures that demand is met at the lowest possible cost. All bids are ranked from lowest to highest in what is known as the merit order. In this order, low-cost renewable generation is placed on the left, while more expensive fossil fuel plants appear on the right. The price for each hour is set by the highest bid needed to meet demand in that hour, known as the marginal unit. Unlike forward and futures markets, where electricity is traded financially without physical delivery, the DAM is where actual supply and demand are matched. Only Balance Responsible Parties (BRPs), or participants with a contract with a BRP, are allowed to trade on the DAM [26].

In the Netherlands, Balance Responsible Parties (BRPs) submit hourly volume-price bids for the Dutch bidding zone through the trading platforms of either EPEX SPOT or Nord Pool [27], [28]. BRP's have until 12.00 CET to submit their bids. This bidding process occurs simultaneously across all European bidding zones. All national power exchanges forward the collected bids to the central European market coupling algorithm, EUPHEMIA, as part of the Single Day-Ahead Coupling (SDAC). This algorithm matches supply and demand across all participating countries while respecting cross-border transmission constraints. The outcome of this pan-European day-ahead auction is a set of market clearing prices for each bidding zone and an optimized allocation of cross-border electricity flows for every hour of the following day. [29] Normally, clearing prices are announced at 12.45 CET or later. After the market clearing, BRP's have the physical obligation to deliver or consume the sold or bought volumes within respective hour.

Intraday Market
After the day-ahead market (DAM) clears, the Dutch intraday continuous market opens at 14:00 CET. This market enables continuous trading of 60-, 30-, and 15-minute contracts up to the start of the delivery period. Unlike the DAM, which is cleared through a single auction, the intraday continuous market operates through bilateral trading. When two matching orders are submitted, a trade is immediately executed. In the Netherlands, intraday continuous trading is possible on three platforms: EPEX spot, Nordpool and ETPA. [27], [30], [31]

Since 2018, the Single Intraday Coupling (SIDC, formerly XBID) has enabled cross-border intraday trading across participating European countries. Bids from different bidding zones are placed on a shared order book. The highest buy order is matched with the lowest sell order, provided sufficient cross-border transmission capacity is available. SIDC aims to increase market liquidity, improve the efficiency of short-term trading, and facilitate the integration of renewable energy by allowing market participants to adjust their positions closer to real time.[32]

In addition to the continuous market, there is also an intraday auction market, which functions similarly to the DAM. National power exchanges aggregate bids and offers and submit them to the SIDC algorithm for market clearing. There are three scheduled intraday auctions per day [33]:

- IDA 1: 15:00 CET on the day before delivery (covers all periods of the delivery day)
- IDA 2: 22:00 CET on the day before delivery (covers all periods of the delivery day)
- IDA 3: 10:00 CET on the delivery day (covers delivery periods between 12:00 and 24:00 CET)

Intraday markets allow balance responsible parties (BRPs) to adjust their positions from the DAM based on updated forecasts, unexpected outages, or changes in expected demand. Together, the day-ahead and intraday markets constitute the spot market. After the intraday market closes, any remaining deviations from a BRP's the e-program are settled with the transmission system operator (TSO), based on the imbalance price. In some cases, BRPs can still adjust their final position after delivery but before settlement with the TSO, by trading on the ex-post market, as explained in the next section.

Ex-Post Market
In the Netherlands, the Ex-Post (ETPA) or After Market (EPEX Spot) is a post-delivery market that allows Balance Responsible Parties (BRPs) to correct imbalances after physical delivery, but before final settlement with TenneT. This market operates outside regular exchange trading hours and offers BRPs a final opportunity to align their contracted volumes with actual production or consumption. On the day after delivery, trading is possible until 9:30 a.m. on ETPA and until 8:00 a.m. on EPEX Spot. [34], [35]

The Ex-Post Market is valuable during Regulation State 2 (RS2), when both upward and downward regulation are active and TenneT applies dual pricing. This results in a spread between the imbalance prices for surplus and shortage, creating an opportunity for BRPs to trade their residual imbalances more favorably. By settling these imbalances with other BRPs, they can avoid the less advantageous imbalance tariffs imposed by TenneT. [34]

ETPA and EPEX Spot have offered Ex-Post or After Market trading products since 2020 and 2021 respectively, making them relatively new. However, traded volumes are increasing rapidly, reflecting the growing number of RS2 quarters and the rising need for flexible post-delivery correction mechanisms.

Timeline of the wholesale markets
Figure 2 summarizes the timeline of the wholesale markets. These markets are active before and after delivery. During delivery, the balancing and congestion markets become active. For this

research we leave the congestion market out of scope as we focus on the balancing market, which is discussed more elaborately in the subsequent section.

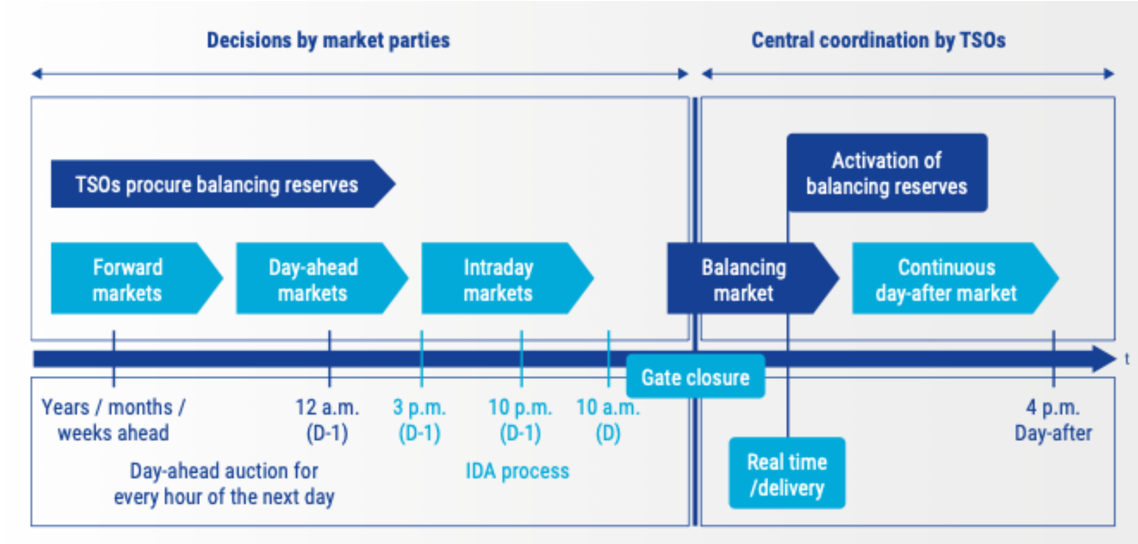


Figure 2: Timeline of the wholesale markets [36]

2.5 The balancing system

This section provides an overview of the Dutch electricity balancing system. It begins by introducing the three main categories of balancing reserves used by TenneT: Frequency Containment Reserve (FCR), Automatic Frequency Restoration Reserve (aFRR), and Manual Frequency Restoration Reserve (mFRR). Each product is discussed individually, along with its specific role in maintaining system stability. Next, the section introduces the international European cooperation platforms PICASSO and IGCC, which play a key role in cross-border coordination and balancing efficiency. Finally, the operational structure and timeline of the balancing process are outlined, including the interactions on Dutch and European level.

Frequency Containment Reserve (FCR)

The Frequency Containment Reserve (FCR), formerly known as primary reserve, is the first layer of frequency control in the Dutch electricity balancing system. It is automatically activated within 30 seconds in response to frequency deviations from the nominal 50 Hz and is designed to stabilize the entire synchronously connected European grid (see *Figure* 4). Procurement of FCR is coordinated at the European level through the FCR Cooperation, a joint platform of TSOs, including TenneT, that organizes daily auctions for symmetric 4-hour capacity products [37]. Bids should have a minimum required power of 1 MW and should be symmetrical. Pooling of units is allowed to reach the minimum 1 MW requirement. During large and long frequency deviations, units should be able to sustain activation for a minimum of 30 minutes. Bids from all participating countries are pooled into a common merit order, with contracts and delivery managed at the national level. Each TSO is required to contribute a share of the total FCR capacity based on its relative share of net electricity production and consumption in the synchronous area. For the Netherlands, this contribution has been approximately 110–123 MW in recent years, of which at least 30% must be sourced from within the Dutch control zone [38]. The remaining capacity can be sourced from the cooperating FCR countries as shown in *Figure* 3. FCR providers are compensated for availability, not energy delivery. FCR activations occur automatically based on real-time frequency deviations. Capacity prices are based on the highest awarded Dutch capacity bid for each 4-hour block or the cross-border marginal price if higher. Dutch FCR capacity is often more expensive than foreign capacity, leading to substantial imports, though domestic battery storage is expected to play a growing role, making FCR less dependent on expensive gas-fired plants. [3], [39]

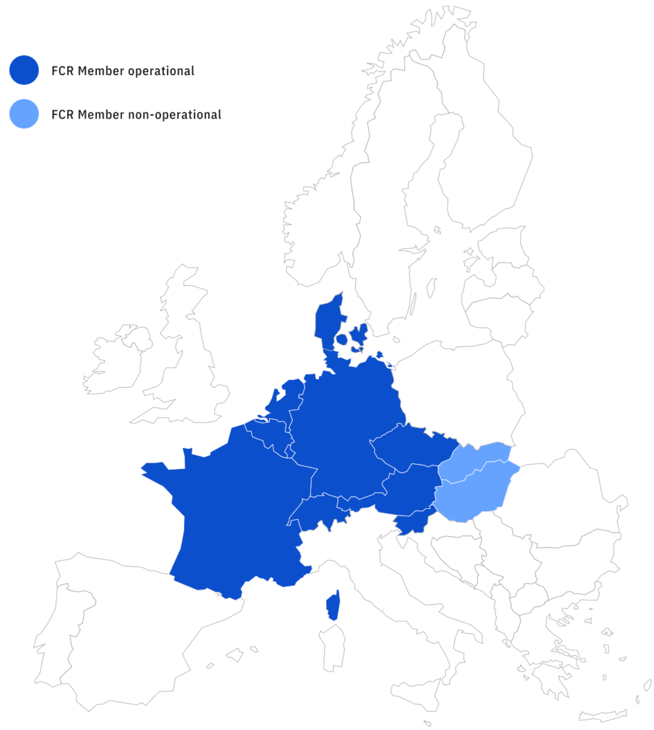


Figure 3: Map of Frequency Containment Reserve (FCR) cooperation members [37]

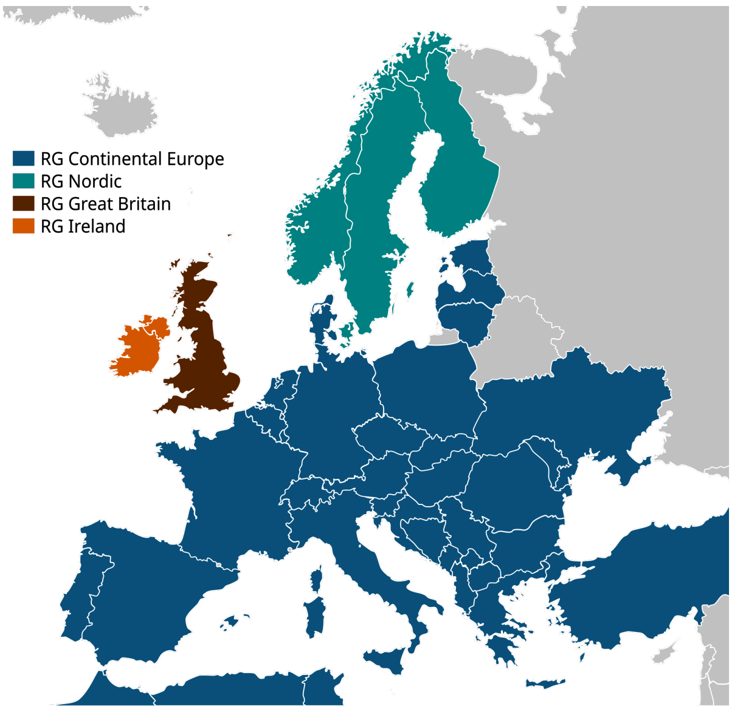


Figure 4: Map of Continental Europe Synchronous Area members [40]

Automatic Frequency Restoration Reserve (aFRR)

Automatic Frequency Restoration Reserve (aFRR) is the second line of defense for maintaining system balance in the Dutch electricity grid. It is activated by the Transmission System Operator (TSO), TenneT, to correct short-term imbalances and stabilize frequency. Unlike Frequency Containment Reserve (FCR), which is activated across the entire synchronous European grid, aFRR is coordinated nationally. With the increasing share of decentralized and weather-dependent generation, aFRR is of great importance to maintain the system balance. [41]

TenneT contracts a minimum volume of aFRR capacity to ensure that enough flexible power is available to respond continuously to real-time imbalance signals. The minimum required volumes from recent years are presented in *Table 17* in Appendix B and show a steady increase. This capacity is procured through a daily blind pay-as-bid auction, which closes at 9:00 a.m. the day before delivery. Balancing Service Providers (BSPs) awarded capacity must submit energy bids for each Imbalance Settlement Period (ISP) by 2:45 p.m. the same day. These bids can be adjusted in price up to 25 minutes before the start of the ISP. All bids must be at least 1 MW in size, and BSPs must be able to deliver the contracted capacity at full power for the full 24-hour delivery period, though this requirement is expected to be reduced to four hours in the future. Currently, the 24-hour requirement is challenging for battery-based assets. [42], [41]

In addition to contracted capacity and associated energy bids, prequalified BSPs are allowed to submit so-called "free bids" without prior capacity obligations. These can also be placed up to 25 minutes before the relevant ISP, with full freedom in price and volume, though they must be at least 1 MW. BSPs may submit up to three bids smaller than 4 MW, in steps of 1 MW. Both contracted and free bids are placed on the same merit-order ladder, without priority given to either category. [41]

The amount of aFRR power to be activated is determined every four seconds by the Load Frequency Controller (LFC), which sends setpoint deltas to BSPs and prequalified participants. Once a bid is activated, the unit must follow the real-time control signal throughout the ISP. The initial response to a setpoint change must be visible within 30 seconds and reach at least 100 kW. Within 60 seconds, the full requested power should be delivered, allowing for deviations between -10% and +20%. The average delivered power over the activation period must match the requested volume. Setpoints for upward and downward regulation are issued separately, and ramp-up and ramp-down constraints are considered during activation. Both upward and downward bids can be activated within the same ISP, depending on system needs. [41]

BSPs are compensated only for the actual activated energy, not for the reserved capacity. Real-time metering is used to monitor delivery performance, and reference signals must be sent every 1 to 4 seconds. Deviations between instructed and delivered power may result in penalties or reduced payments. TenneT publishes activation volumes and prices at the four-second resolution in the middle block of each minute [43]. Due to ramp constraints, the published price may not align exactly with the activated volume. For settlement, BSPs must allocate their delivered energy to specific metering points (EANs) per five-minute block. Finally, the total activated volume is remunerated at the marginal price for upward and downward regulation separately. If both upward and downward energy were activated within the same ISP, each is compensated at its own respective activation price, as published by TenneT. [41]

Manual Frequency Restoration Reserve (mFRR)

Manual Frequency Restoration Reserve (mFRR), formerly known as tertiary reserve, is a balancing product activated manually by TenneT in response to major incidents or persistent power system deviations. Unlike aFRR, which operates automatically, mFRR is triggered by the TSO based on system needs and is used as a last resort to restore balance over longer timeframes. [44]

Providers of mFRR must be able to deliver the contracted capacity continuously for the full contract period, which currently spans 24 hours. Like with aFRR, there are plans to reduce this period to four hours to better accommodate flexible assets such as batteries. Participation is dominated by large industrial consumers and horticultural businesses, which have sufficient controllable load or generation capacity. [44]

The mFRR market operates based on capacity contracts without a bid obligation. This means participants must always maintain their committed capacity but are only activated when TenneT requires additional reserves. Activation does not follow a merit order, instead, contracted volume is directly activated based on the system's needs. Participants receive pay-as-bid remuneration for both the reserved capacity and the energy delivered to or withdrawn from the system during activation. [44]

Table 3: Overview of FCR, aFRR and mFRR characteristics based on [39], [41], [44]

Product	FCR	aFRR	mFRR
Market type	Primary reserve	Secondary reserve	Incident reserve
Activation method	Automatic	Automatic	Manual
Procurement – capacity	Contracted	Contracted	Contracted
Remuneration for	Contracted capacity	Contracted capacity (bid obligation) and activated energy bids	Contracted capacity and activated energy bids
Minimum availability capacity	4 hours	24 hours (will become 4 hours)	24 hours (will become 4 hours)
Minimum capacity	1 MW upward and downward	1 MW upward and downward	1 MW upward and downward
Symmetrical capacity bid	yes	no	yes
Symmetrical energy bid	-	no	-

2.6 Overview of the balancing process

Figure 5 illustrates the balancing process as described by TenneT in [45]. It consists of three main phases:

- Preparation day ahead (D-1): On the day before delivery, each Balance Responsible Party (BRP) submits its commercial trade schedule for the next day. TenneT checks whether these combined schedules ensure that supply and demand are balanced for every 15-minute Imbalance Settlement Period (ISP).
- Delivery day (D): This is when electricity is actually injected into or withdrawn from the grid. BRPs are expected to follow their submitted schedules. If an imbalance arises, TenneT activates balancing resources to restore the system within 15 minutes. BRPs can still adjust their schedules up to four ISPs before delivery, while Balancing Service Providers (BSPs) can modify their bids up to two ISPs ahead.
- Settlement (D+1): From 10:00 a.m. on the day after delivery, TenneT calculates and publishes the settlement prices, determines each BRP's imbalance, and settles these financially.

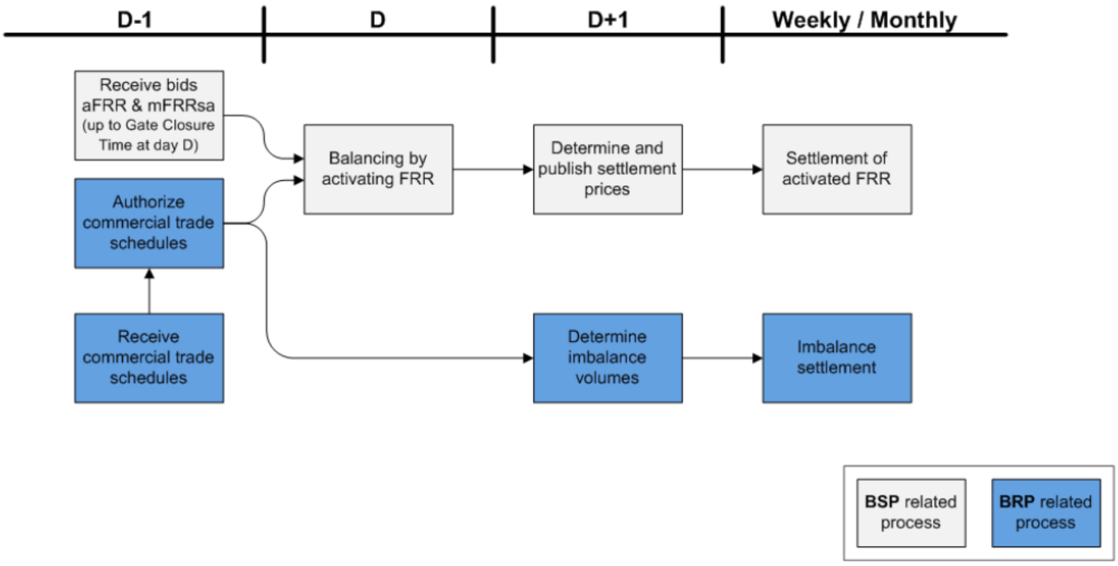


Figure 5: Overview of the balancing process from the day ahead of delivery till settlement [46]

2.7 PICASSO and International Grid Control Cooperation (IGCC)

In Europe, the PICASSO platform (Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation; see *Figure* 7 for participating countries) manages the cross-border activation of aFRR (automatic Frequency Restoration Reserves), while IGCC (International Grid Control Cooperation) performs imbalance netting across synchronous areas.[24], [47]

TenneT, as part of both platforms, submits real-time aFRR demand from the Dutch LFC area to the PICASSO system. The PICASSO algorithm, using a Common Merit Order List (CMOL), optimizes bid selection and aFRR demand distribution across all participating LFC areas. It incorporates both economic efficiency and congestion management, operating in 4-second optimization cycles. [47]

The result of this optimization is a correction value, which is returned as an input to TenneT's notational LFC controller. This correction adjusts the initial local FRCE-based (Frequency Restoration Control Error) aFRR demand. The corrected demand is then used by the Dutch aFRR controller to generate actual activation setpoints, ensuring the Dutch system responds appropriately to cross-border optimization decisions. [47]

Following PICASSO, the IGCC process performs explicit imbalance netting, further optimizing the LFC inputs of TSOs not fully participating in PICASSO. A final step runs the PICASSO algorithm again to align the result with the updated system state. This sequence in shown in *Figure* 6 and ensures that:

- aFRR demand is input to the AOF (Activation Optimization Function),
- the AOF + IGCC output generates correction values,
- these corrections modify the LFC input for each TSO,
- and TenneT's local LFC controller activates local reserves accordingly.

Although the PICASSO platform determines which bids are selected from the CMOL, the Cross-Border Marginal Price (CBMP) calculated by PICASSO is not used directly to set the national aFRR prices in the Netherlands. Instead, Dutch aFRR prices continue to be determined solely by the highest (upward) or lowest (downward) activated bid from the local merit order list. [45], [48] However, PICASSO does influence which volumes are activated and in which direction. This affects the local power imbalance and thus indirectly impacts Dutch imbalance prices. For example, if PICASSO results in fewer local activations, this can lower imbalance prices. Conversely, more local activations triggered by PICASSO optimization may shift the regulation state or lead to higher imbalance prices. [45], [48]

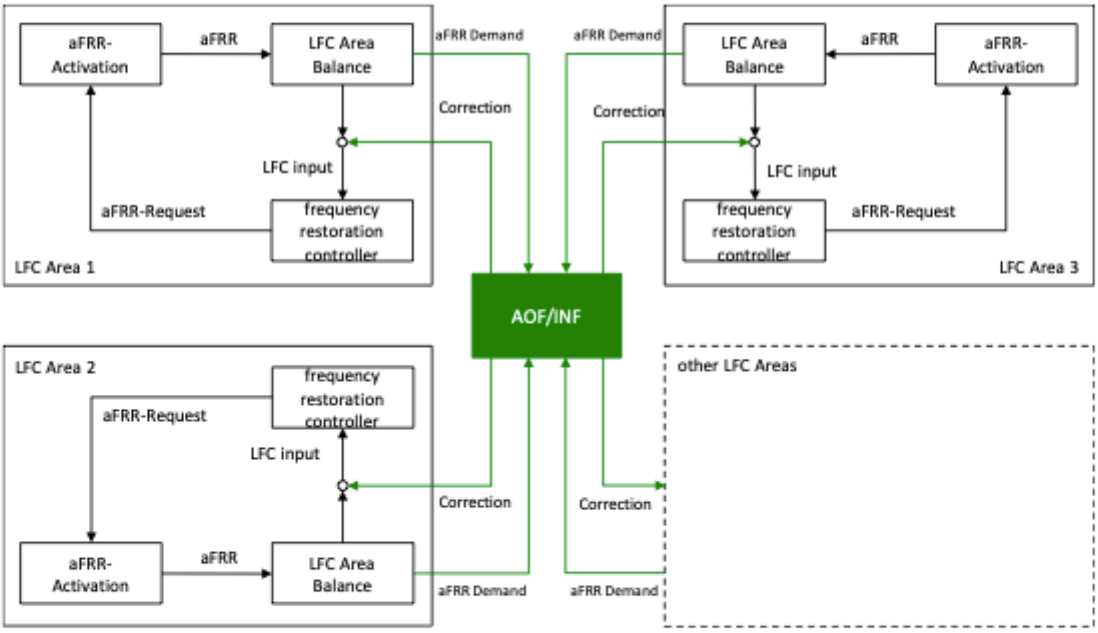


Figure 6: High level design of interaction between Activation Optimization Function (AOF) and Load Frequency Control areas [47]

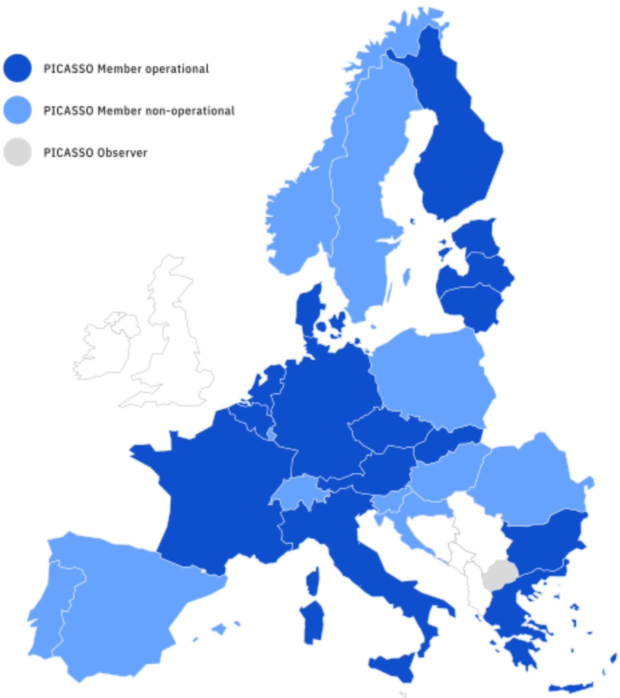


Figure 7: Map of PICASSO members (as of April 2025) [24]

2.8 Imbalance pricing system and regulation states

The imbalance pricing system is extensively described by TenneT in [45] , and can be roughly summarized as follows.

In the Netherlands, imbalance settlement is based on a marginal pricing system that applies a uniform price per direction, per Imbalance Settlement Period (ISP). This means that for each ISP, all activated balancing energy in the same direction is settled at the same price, determined by the highest activated upward bid or the lowest activated downward aFRR bid, or by the mFRR price if that is more extreme. If no balancing energy is activated in an ISP, the imbalance price reverts to the mid-price calculated from the merit order, or defaults to the previous ISP's imbalance price.

The imbalance pricing system plays a crucial role in incentivizing Balance Responsible Parties (BRPs) to maintain system balance. A BRP's imbalance, defined as the deviation between its final position and its last approved commercial trade schedule, is settled financially using imbalance prices that apply to either BRP shortages or BRP surpluses. For each ISP, there are effectively two imbalance prices: one for BRP shortages and one for BRP surpluses. Whether these are the same or different depends on the regulation state.

Regulation states
TenneT distinguishes four regulation states, which determine how imbalance prices are calculated and applied:

- Regulation State 0 (RS0): No activation of balancing energy by TenneT in the ISP. In this case, both BRP shortages and surpluses are settled at the mid-price (the average of the lowest upward bid and the highest downward bid in the merit order).
- Regulation State 1 (RS1): Only upward balancing energy is activated. Both BRP shortages and surpluses are settled at the upward balancing energy price (the highest activated upward bid or, if higher, the mFRR price).
- Regulation State -1 (RS-1): Only downward balancing energy is activated. Both BRP shortages and surpluses are settled at the downward balancing energy price (the lowest activated downward bid or, if lower, the mFRR price).
- Regulation State 2 (RS2): Both upward and downward balancing energy are activated within the same ISP. In this situation, the imbalance prices for shortages and surpluses usually differ. Reverse pricing can apply: if the upward balancing energy price is below the mid-price, the mid-price is used for settling BRP shortages; similarly, if the downward balancing energy price is above the mid-price, the mid-price is used for settling BRP surpluses. This ensures sharper financial incentives for BRPs to contribute to system balance.

The determination of these regulation states is based on the profile of the balance delta (the difference between activated upward and downward volumes) within the ISP. If this series increases or remains constant throughout, RS 1 applies; if it decreases or remains constant, RS-1 applies; if it both increases and decreases, it is classified as RS2.

Impact on BRPs
This framework directly shapes how BRPs are financially exposed to their imbalances. It means that depending on the regulation state, a BRP pays or receives an amount for its shortage or surplus at the applicable imbalance price for that position. In most ISPs (RS 0, 1, or -1), the prices for shortages and surpluses are identical. Only in RS2 can these prices diverge, providing a clear incentive to avoid contributing to system imbalances in either direction.

Overall, this mechanism ensures that BRPs are financially motivated to actively support system balance, either by aligning their portfolios to minimize imbalance or by strategically responding to real-time price signals. The design of these imbalance prices, and how they vary with the regulation state, is thus a key element for both passive balancing and in shaping the economics of aFRR participation, which is a central topic of this thesis.

3 Methodology

This chapter details the research methodology, which is structured to systematically answer the sub-questions and, ultimately, the main research question. The approach combines a qualitative case study, quantitative data analysis, and simulation modeling.

3.1 Answering SQ1: passive balancing analysis

SQ1: *How does the currently used passive balancing strategy of Zonneplan work and how does it perform under the growing frequency of Regulation State 2 ISPs?*

To answer this first sub-question a mixed-method approach was used:

Qualitative Case Study: The operational logic of Zonneplan's passive balancing strategy was documented through a case study approach. Information was gathered from internal documentation and discussions with Zonneplan employees, providing a detailed, albeit simplified, overview of their system architecture, price forecasting models, and asset optimization process. This provides the necessary context to understand the mechanics behind the performance data.

Quantitative data analysis: Section 4.4 presents an analysis of passive balancing results covering the period from January 2024, when Zonneplan began with passive balancing, to March 2025, which the start of this research. Although the available data is limited to 15 months (in fact 14, as there is no data for October 2024) and lacks statistical significance, the inclusion of the first three months of 2025 enables year-on-year comparison and helps identify emerging trends. Data was extracted from Zonneplan's database using SQL queries. The analysis was conducted in Jupyter Notebooks, using Python with Pandas for data analysis and manipulation, and Matplotlib for visualization.

With respect to the analysis of the **backcast** performance the following point are considered:

- The passive balancing backcast is based on a simulated control strategy for a single theoretical home battery with a power capacity of 10 kW and an energy capacity of 20 kWh, as this is the most common battery in Zonneplan's aggregated pool of batteries and is considered the most optimal configuration. To enable a fair comparison with the aFRR bid simulation results, all delivered volumes were scaled by a factor of 100. This effectively represents a pool of 100 identical batteries, with a combined power capacity of 1 MW and a total energy capacity of 2 MWh.
- The main output of the backcast is the net power delivered per minute, referred to as the net volume. By summing the net volumes over each 15-minute Imbalance Settlement Period (ISP), the net position per ISP is calculated. This is then used to determine the financial result per ISP based on the applicable imbalance price. To reflect the effect of Ex-Post trades and internal or BRP portfolio advantages (PA), an adjusted imbalance price is used for RS2 quarters. The resulting financial value is referred to as Revenue Incl. Ex-Post and PA and provides a more realistic representation of the financial performance of passive balancing as it improves the results of RS2 ISPs. The term revenue is used throughout, although charging and discharging may also involve costs. Referring to it as profit would be misleading, as not all cost components are included in the analysis.
- Because theoretical backcast data is used, the delivered output is exactly equal to the desired output. In reality, household electricity consumption could trigger Dynamic Load Balancing (DLB), limiting the battery's maximum power, but this constraint is also excluded

from the aFRR simulations in Chapter 6 in order to provide a consistent basis for comparison with passive balancing data. However, this assumption might slightly overestimate available power and revenue potential. The backcast results also assume no technical failures or disruptions as it focusses on theoretical potential. A charging and discharging efficiency of 100% is assumed, along with a Depth of Discharge (DoD) of 93%. The balance delta delay is fixed at 5 minutes for the entire simulation period to support meaningful monthly comparisons. Although this delay was only implemented in practice from October 2024 onward [11], it is applied throughout the entire backcast. October is excluded from the results due to missing input data.

This analysis establishes a performance baseline for the passive balancing strategy, which is crucial for the comparative analysis in Chapter 6.

3.2 Answering SQ2: aFRR market analysis

SQ2: *What are the current trends in the aFRR bidding ladder, prices and volumes?*

To answer this second sub-question, the following data source and methodology was used.

Data Source: Chapter 5 presents a market analysis of the aFRR market. The analysis is based on data obtained from TenneT's transparency download page [49], which includes the following:

- Settlement prices with ISP-level resolution, including Price Dispatch Up and Down.
- Volume of Settled aFRR.
- Merit order list aFRR: Bidding ladder per ISP with prices in steps of 10 MW for both Upward and Downward bids.

For the data on contracted capacity prices and volumes data from a table from the Rabobank report [3] has been supplemented with data from ENTSO-E [46].
Method of Analysis: The analysis was performed using Python (Pandas, Matplotlib) to process and visualize the data. The investigation focused on identifying trends in:

- The structure of the aFRR bidding ladder and its evolution over time. Reveals how competition, market size and maximum and minimum prices have evolved over time which helps to understand current and future market potential.
- Contracted capacity prices and volumes. Although participation in the contracted capacity market is not included in the simulations, it is a good indicator of the size and growth of the entire aFRR market.
- Activated energy volumes and the corresponding dispatch prices (upward and downward). To reveal current and future potential of activation of upward and downward bids.
- Price duration curves and daily price patterns to reveal opportunities for bidding strategies.
- The frequency of price peaks and their occurrence across different regulation states. To understand the difference in performance with passive balancing.

3.3 Answering SQ3: aFRR bid strategy simulation

SQ3: *What are possible Bidding strategies for Zonneplan to participate in the Dutch aFRR market and how do they perform?*

To address the third and final sub-question, a simulation model was developed in Python, using Jupyter Notebooks and Pandas Library, to explore and assess the financial performance of various

aFRR bidding strategies using historical market data under different parameter settings and Dutch market conditions.
The simulation model relies on input data obtained from TenneT's download transparency page [49], which includes:

- Historical balance delta data, including minute-level information on activated upward and downward aFRR volumes, the highest upward regulation price, mid-price, and lowest downward regulation price.
- Settlement prices with ISP-level resolution, including activated upward and downward prices, as well as the corresponding regulation state.

The next sections explain the logic behind the simulation run, detailing the bid strategy and timeline applied within the model.

3.3.1 Simulation model

Figure 8 presents a schematic overview of the simulation model. The simulation can be divided into three main processes: Bidding, Activation and the Settlement. The model incorporates various components including battery parameters, market input variables, as well as State, decision and output variables. Table 4 on the next page provides a complete overview of the main components of the simulation model, which will be referenced in the explanation of the main processes in the following sections.

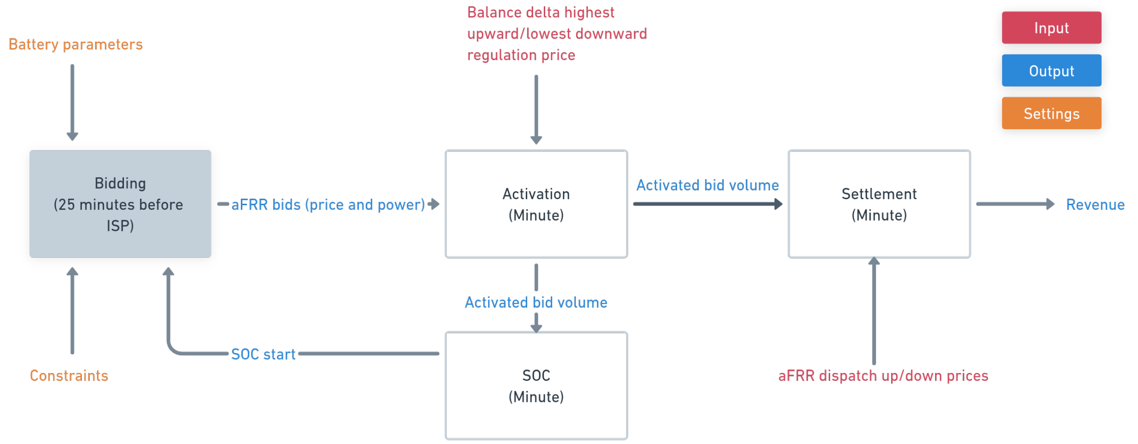


Figure 8: Schematic overview of the simulation model including the three main processes of Bidding, Activation and Settlement

Table 4: Overview of the simulation model parameters and variables

Term	Description	Type	Value	Unit
Battery Capacity	Energy capacity of the battery	Input parameter	20.0	MWh
Battery Power	Max power of the battery	Input parameter	10.0	MW
Initial SoC	Initial State of Charge; initial energy level in battery	Input parameter	10.0	MWh
DoD	Depth of Discharge	Input parameter	93	%
Round-trip efficiency	Battery charge/discharge cycle efficiency	Input parameter	85	%
SoC Buffer	Buffer to protect SoC overshoot	Input parameter	0.35	MWh
Power per min	Volume delivered in 1 minute per MW of power (1/60)	Input parameter	0.01667	MWh
Degradation costs	Battery degradation costs for both charging and discharging	Input parameter	25	€/MWh
Upward bid price	Price for upward regulation bids	Input parameter	-	€/MWh
Downward bid price	Price for downward regulation bids	Input parameter	-	€/MWh
Price Dispatch Up	Settlement price for upward regulation in an ISP	Market input variable	-	€/MWh
Price Dispatch Down	Settlement price for downward regulation in an ISP	Market input variable	-	€/MWh
Highest Upward Price	Highest activated upward bid price per minute	Market input variable	-	€/MWh
Lowest Downward Price	Lowest activated downward bid price per minute	Market input variable	-	€/MWh
SoC Start	State of Charge at start of minute	State Variable	-	MWh
SoC End	State of Charge at end of minute	State Variable	-	MWh
Upward Bid	Power capacity of upward bid	Decision Variable	-	MW
Downward Bid	Power capacity of downward bid	Decision Variable	-	MW
Activated Upward Volume	Volume delivered upward (discharged volume)	Output Variable	-	MWh
Activated Downward Volume	Volume delivered downward (charged volume)	Output Variable	-	MWh
Upward Revenue	Revenue from upward activation	Output Variable	-	€
Downward Revenue	Revenue from downward activation	Output Variable	-	€

3.3.2 Bidding logic

The first process of the simulation model is the bidding process which simulates how bids are submitted every 15 minutes, starting at minute 5, and each bid applies to the Imbalance Settlement Period (ISP) beginning 25 minutes later. This timing reflects TenneT's gate closure requirement for aFRR bidding. For example: A bid placed at minute 5 in ISP 1 applies to ISP 3 starting at minute 30. At each bidding moment, the model evaluates whether the battery has enough energy (for discharging) or free capacity (for charging) to remain fully available during 25 minutes of continuous activation of the placed bids. The power capacity for the upward or downward bid is determined as follows:

- For every minute 25 minutes before start ISP (the target ISP) the following is done:
- Determine how much upward and downward energy should be reserved to determine the boundaries in case of full activation in the same direction of all placed bids between time of bidding and the start of ISP:
  - Reserved_energy_up = (power_per_min / one_way_efficiency * future_bid['up'])
  - Reserved_energy_down = (power_per_min / one_way_efficiency * future_bid['down'])

- Based on current SoC, SoC boundaries, reserved energy and the SoC buffer, determine the available energy for bidding:
  - available_energy_up = soc - min_soc - reserved_energy_up - soc_buffer
  - available_energy_down = soc - max_soc - reserved_energy_down - soc_buffer

Then, based on the available energy, the maximum upward bid and downward bid is determined based on bids in steps of 1 MW in a range from 0-10 and by rounding down to the closest possible bid based on the available energy up and down. A bid of 0 is seen as: no bid is placed. Bids are appended to the bid log for each minute or ISP in which they are placed. For the simulations a 10 MW 20 MWh battery, equal to a battery pool of 1000 10 KW 20 kWh batteries is simulated from which the results are scaled with a factor 10 to allow for equal comparison with the backcast results, but also to mirror Tennet's requirement of a 1MW minimum bid size. For future research the parameters can easily be changed to simulate battery pools or stand-alone large-scale batteries with different power and capacity.

For the simulations with constant bid prices, the upward and downward bid price are constant input parameter only used in the activation process. For the bidding strategies based on the intraday and day-ahead prices, the bid price is determined based on a constant margin and the day-ahead price of the respective ISP or the latest available intraday price (25 minutes before ISP) of the respective ISP.

3.3.3 Bid activation

The second process is the bid activation. Unlike the bidding process, which occurs every 15 minutes, activation is evaluated at a one-minute resolution to approximate the continuous nature of aFRR dispatch.

In practice, aFRR activation is driven by 4-second delta setpoints calculated by TenneT's LFC. However, such high-resolution activation data is not publicly available. Instead, TenneT publishes a snapshot of the marginal activation price taken at the midpoint of each minute. This price reflects the highest activated upward bid, or the lowest activated downward bid, at that moment. The simulation uses this minute-level snapshot to determine whether a bid would likely have been activated.

For each minute, the model checks:

If a bid is active in the ISP covering that minute:

- For upward bids: bid['up'] > 0
- For downward bids: bid['down'] > 0

If the marginal upward or downward minute price meets the activation threshold (Bid Price):

- Highest upward price >= upward bid price
- Lowest downward price <= downward bid price

If both conditions are satisfied, the battery is dispatched at the bid power level for one minute. The resulting energy is used to:

- Update the battery's State of Charge (SoC), accounting for one-way efficiency.
- Record the activated volume for financial settlement.

While this approach does not capture the full resolution of real-time control, it provides a reasonable approximation given the available data.

3.3.4 Financial settlement

The final component of the simulation model is the financial settlement. This step occurs within the activation loop and is based on the activated volume per minute. While the simulation uses historical prices, which are fixed across each ISP (15-minute period), this approach yields valid results because the settlement prices are uniform within an ISP.

In operational practice, TenneT calculates settlement prices at the end of each ISP. The Price Dispatch Up is determined by the highest activated upward bid, while the Price Dispatch Down is set by the lowest activated downward bid. If the downward price is negative, TenneT pays the BSP; if positive, the BSP pays TenneT. To reflect this in the simulation, the revenue from downward activation is calculated by multiplying the activated volume with the negative of the Price Dispatch Down. This ensures that positive revenues indicate payment to the BSP, and negative revenues represent costs.

The revenue is calculated as follows:

- **Upward activation**: revenue_up = activated_up_volume × Price Dispatch Up
- **Downward activation**: revenue_down = activated_down_volume × - Price Dispatch Down

3.3.5 Simulation output and KPI's

In summary, the output of the simulation is a per-minute dataset with the following variables:

- soc_start, soc_end: the state of charge (SoC) of the battery at the beginning and end of each time step
- bid_up_active, bid_down_active: the submitted upward and downward bid volumes, ranging from 0 to 10 MW.
- activated_up, activated_down: binary activation flags (TRUE or FALSE), showing whether an upward or downward activation occurred
- activated_up_volume, activated_down_volume: the actual volume activated per direction
- revenue_up, revenue_down: financial results per minute from upward and downward activations

With the output of the simulation, multiple key performance indicators can be computed to compare performance over the entire period and by month. These performance indicators are used in the results section and include the following:

- Revenue upward activation
- Revenue Downward activation
- Total revenue
- Net revenue = Total revenue – (Absolute activated volume * degradation costs)
- Upward activated volume
- Downward activated volume
- Volume weighted average price upward activation = (Revenue upward activation / upward activated volume)
- Volume weighted average price downward activation = - (Revenue downward activation / downward activated volume)

3.3.6 Assumptions

- **Full Minute-level activation based on bid price:**
  If the minute-level aFRR price reaches the bid price, it is assumed that the bid is fully activated for the entire minute and remains active until the price drops below the threshold. This simplification was made due to the lack of higher-resolution activation data from TenneT. While this could slightly overestimate activated volumes in cases of partial or fluctuating activation within a minute, the impact is expected to be minimal. This is supported by a comparison between TenneT's published settled aFRR volumes and activated volumes derived from balance delta data.
- **Activated volume equals delivered and settled volume:**
  The model assumes perfect adherence to dispatch instructions, meaning batteries follow the requested power output exactly. In practice, small deviations can occur due to control delays, unresponsive devices, or congested household grid connections. However, these deviations are assumed to have a negligible effect on performance and are not included in the simulation.
- **No ramp-up/ramp-down time:**
  Batteries are assumed to instantly switch between power levels without delay. Although real systems do exhibit minor ramp constraints and control signal delays, this simplification is unlikely to significantly affect results. The extra volume gained from assuming an immediate ramp-up is largely offset by the volume lost from the assumed immediate stop, resulting in a minimal net impact on total activated energy.
- **Bidirectional switching within an ISP:**
  It is assumed that batteries are capable of switching between upward and downward activation within the same ISP and between consecutive minutes. BSPs can indicate whether such bidirectional activations are technically feasible. Given the fast response times of home batteries, this assumption is considered realistic.
- **Sufficient alternation between upward and downward activation:**
  The model assumes that upward and downward activations alternate frequently enough to allow batteries to charge and discharge exclusively through participation in the aFRR market. This is based on observations from passive balancing, which also relies solely on imbalance price signals. Simulation results confirmed that this assumption generally holds, although Strategy 1a experienced prolonged periods of inactivity due to its consistently high upward bid prices.

3.3.7 Bidding strategies considered in this study

In this study, three bidding strategies were considered to evaluate the potential of aggregated home batteries in the Dutch aFRR market. These strategies were chosen to reflect a range of practical approaches, from simple static bidding to more dynamic and robust methods based on market prices. Bid Strategy 1 explores constant price bidding, which served both as a baseline and as a foundation for developing and validating the simulation model, due to its simplicity and ease of implementation. Bid Strategy 2, introduces Day-Ahead market-based bidding, adding responsiveness to expected price patterns. Bid Strategy 3 builds on this by incorporating the most recent Intraday prices, aiming to improve bid accuracy closer to real-time. Together, these strategies were used to offer a structured comparison ranging from static to more dynamic bidding approaches, each with an increasing level of complexity, and are explained in more detail below.

Bid Strategy 1: aFRR constant bids with (1a) and without (1b) minimum price spread

For the simulation of the first bid strategy, constant bid prices are applied. All bids are submitted at predefined, fixed prices for both upward and downward regulation. If the current state of charge (SoC) and its operational boundaries allow it, the model places a bid for the relevant direction. For instance, upward regulation bids may be submitted at €120/MWh, while downward regulation bids are submitted at €70/MWh.

This strategy has been tested with both a fixed price spread minimum of €50/MWh (**Bid Strategy 1a**) and without a fixed price spread (**Bid Strategy 1b**). A fixed price spread ensures that any energy exchange (charging and subsequent discharging) never results in a net financial loss. However, because the bid price is often not equal to the final Price Dispatch Up/Down, the strategy has also been tested without minimum spread. The results section presents the optimal combination of bid prices for maximizing net revenue, identified by looping the simulation through all possible price combinations within the range of -€300 to €300 in steps of €10 for both upward and downward bids.

Bid Strategy 2: Day-Ahead price-based bidding

The comparison of Day-Ahead (DA) prices with the average Price Dispatch Up and Down in Chapter 5 reveals an interesting daily pattern. To exploit this and enable more dynamic bidding, ISP-level bids in Bid Strategy 2 are linked to the corresponding hourly DA price which ensures activation only takes place for prices that match the value at that time. For instance, at the beginning and end of the day, the average Price Dispatch Up is considerably higher. Bidding too low during these periods would lead to excessive activation at relatively lower prices, which is suboptimal. To avoid this, bids are placed higher, aligned with the DA price, which also shows peaks during these times, allowing the strategy to better capture high price peaks. Conversely, during midday, the average Price Dispatch Up is lower. Bidding too high in this period would result in little to no activation. Therefore, slightly lower bids are placed, again based on the lower DA prices at that time, to increase the chance of activation. Meanwhile, the average Price Dispatch Down is also lower around midday, allowing for cheaper charging and maintaining an attractive price spread. By using Day-Ahead prices as a reference, the strategy not only aligns with typical daily price movements but also becomes more adaptive to structural changes in market dynamics.

Because bidding exactly at the DA price may not be optimal, a fixed margin is added to the DA price for both upward and downward bids. This keeps the bid prices dynamic while it allows to find a margin that results in more optimal results. As in Bid Strategy 1 with constant bid prices, the optimal margin is identified by simulating all values in the range from -€300 to €300 in €10 increments.

Bid Strategy 3: Intraday price-based bidding

As a third bid strategy, the potential of using the latest available intraday price at 25 minutes before the start of each ISP is explored. This approach is based on the hypothesis that the most recent intraday price serves as a reliable predictor of the corresponding upward and downward aFRR prices. The use of Intraday prices as input for imbalance price forecasting by Zonneplan served as the main inspiration for this strategy.

Since bidding exactly at the intraday price is also not necessarily effective, the Intraday price is used as a dynamic reference point. As with the previous strategy, an optimal upward and downward margin is determined by simulating a range of margin values. For both the DA and ID prices, datasets from Zonneplan were used.

3.3.8 Model validation and verification

To assess whether the simulation model can provide meaningful insights into the performance of batteries bidding into the aFRR market and can accurately reflect activation dynamics, multiple validation steps were taken:

- Monthly revenue is compared with monthly average upward and downward prices: Months with high average upward prices are expected to have higher revenue, especially when combined with a low average downward price.
- Monthly revenue is compared with monthly price volatility: Months higher price volatility is expected to result in higher revenue.
- Monthly revenue is compared with the passive balancing backcast results as they are expected to show a similar patten because the imbalance prices are essentially based on the aFRR upward and downward prices.
- Monthly SoC dynamics are visualized and assessed to validate the monthly revenues. Months with long prolonged periods of only or mostly activation into one direction leads to less activation. For example, when for a long period there is only upward regulation, the battery is likely to become completely empty, only allowing to place bids for downward regulation. However, if no downward regulation is activated for a long time, this could lead to very little battery activity. In lower revenue months, like in January 2024, this seems to happen more frequently as for example around January 9th as visualized in *Figure 9*.
- With *Figure 9*, it was validated if the model was able to capture the extreme price peaks by looking at SoC dynamics, revenue and the minute resolution highest activated upward and lowest activated downward activation prices.

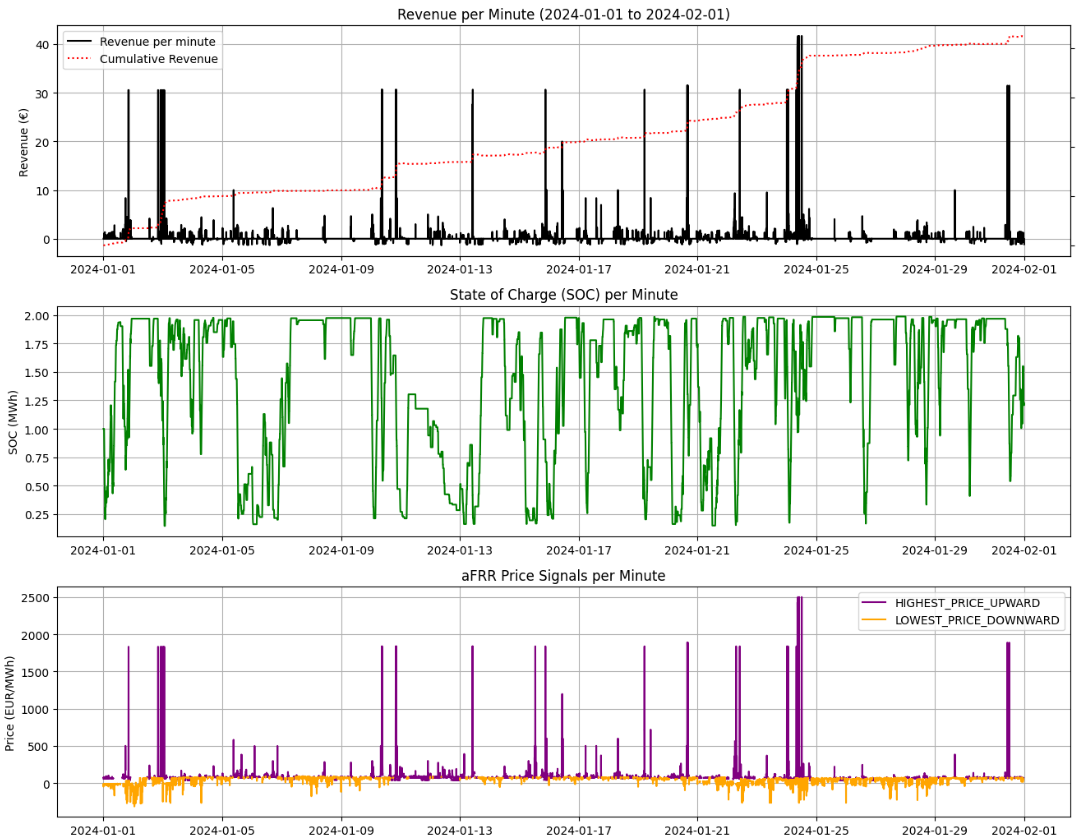


Figure 9: Revenue, SoC and aFRR upward and downward prices per minute (January 2024)

Additionally, the following verification steps were undertaken to ensure that the model is correctly built:

- Manual calculations to verify if the SoC constraints are correctly applied in the bidding process.
- Manual check to verify that the correct SoC end is taken over as next minutes SoC start.
- Manual checks whether the highest upward regulation price and lowest downward regulation price correctly trigger bids depending on the bid prices.
- Manual calculation to verify whether the SoC is correctly updated by the activated upward or downward volume.
- Manual calculations to verify whether the ISP Dispatch Up and Dispatch Down are correctly applied in the revenue calculation.
- Manual check to verify that activated downward volume at a positive Price Dispatch Down leads to negative revenue.
- Manual check to verify that applying charge and discharge efficiency lead to more charged volume compared to discharged volume.

4 Passive Balancing Analysis

This chapter outlines the passive balancing approach used by Zonneplan. The described method reflects Zonneplan's strategy from early 2024 to approximately May 2025. While the explanation is slightly simplified, it provides a representative overview of their operational approach.

Next, the growing frequency of RS2 occurrence is briefly discussed after which the key insights from the analysis of Zonneplan's passive balancing backcast are presented. This includes the impact of RS2 on revenue, the charge and discharge volumes across regulation states, and the benefits of Ex-Post and portfolio advantages for RS2 ISPs.

This chapter addresses Sub-Question 1 and provides input for the comparison with the aFRR bid simulation results discussed in Chapter 6.

4.1 Involved actors and settlement

Zonneplan engages in passive balancing by strategically adjusting the net position of its portfolio during each Imbalance Settlement Period (ISP) based on expected imbalance prices. The underlying mechanism for this strategy is the imbalance settlement system, as outlined in Chapter 2.

To execute this strategy, Zonneplan is connected to a Balance Responsible Party (BRP). Zonneplan does not submit its own e-program to TenneT. Instead, this is handled by the BRP, who manages a broader portfolio comprising positions from multiple market participants. Zonneplan's internal portfolio is divided into two components: one part includes all energy customers, covering both solar PV generation and expected consumption. The other part consists of a neutral position representing the controllable home batteries.

This study focuses specifically on the home batteries. Therefore, only the position of the home battery portfolio is considered. *Figure 10* illustrates the relationship between TenneT, the contracted BRP, Zonneplan, and the individual customers who own home batteries.

Figure 10: Passive Balancing Involved Actors and flows

The resulting imbalance positions, taken strategically by Zonneplan's home battery portfolio, are first settled between TenneT and the BRP. The BRP then settles with Zonneplan, and Zonneplan subsequently settles with its customers.

Two distinct flows can be identified in this process. The first is a right-to-left flow in which shows the communication with regard to the net position per quarter of the day. Although this position is neutral, it represents the expected behavior of the portfolio and forms the basis for market participation. This e-program must be submitted daily.

The second flow from left-to-right represents the financial settlement. While settlement is based on ISP-level positions and prices, the actual financial transaction occurs monthly. The BRP settles with TenneT for the entire portfolio, with the direction of payment depending on the net result. The BRP also settles with Zonneplan. Historically, this monthly settlement has always resulted in a positive financial flow from the BRP to Zonneplan. Finally, Zonneplan distributes revenues to its customers who own home batteries, based on their individual contributions to the aggregated portfolio position. Although these customers do not interact with the market directly, they receive compensation from Zonneplan for the energy their batteries charged and discharged in support of the passive balancing strategy.

In Regulation States 1, -1, and 0, settlement per ISP is straightforward as the same imbalance price applies to both shortages and surpluses. The imbalance price is directly applied to the net imbalance position. However, during Regulation State 2, dual pricing creates arbitrage opportunities. Zonneplan can mitigate the associated risks by adjusting its net ISP-position through Ex-Post trading on the ETPA platform, allowing it to minimize exposure to unfavorable imbalance prices after real-time.

Once the net imbalance positions are finalized, Zonneplan can further improve its RS 2 net imbalance position by leveraging the contractual structure with the BRP and the internal composition of its portfolio. Two key advantages emerge:

- **Internal portfolio advantage**: Within Zonneplan's portfolio, imbalances from customer load and from the aggregated home battery portfolio can offset each other when they are in opposite directions.
- **BRP portfolio advantage**: The BRP manages a broader client portfolio and can net out imbalances across portfolios. This enables additional advantages when Zonneplan's imbalance position crosses out favorably with other portfolios within the BRP portfolio.

In section 4.4, the impact of these advantages on the monthly results are presented and discussed. But first, the next section 4.2 describes the system and approach used by Zonneplan to optimize its strategic out-of-balance positions.

4.2 Zonneplan's passive balancing system

This section presents a short overview of the simplified passive balancing strategy used by Zonneplan. First the technical components are discussed after which the optimization approach is described with a system diagram.

4.2.1 Technical components

The Zonneplan Nexus home battery system is built around lithium-ion battery modules supplied by Pylontech. These batteries come in 10, 15, and 20 kWh configurations. The design is modular, with stackable 5 kWh units, allowing for easy expansion. The majority of the deployed systems in Zonneplan's fleet use the 20 kWh version. The subsequent analysis in this chapter is based on this configuration.

The system also includes a hybrid inverter, which converts DC electricity from the battery to AC for household use and grid interaction. The inverter has a maximum charge/discharge rate of 10 kW. This high-power rating enables the battery to respond rapidly to imbalance price signals. At full power the battery can fully charge or discharge within two hours. The inverter communicates via a 4G connection with both the household's smart meter and Zonneplan's asset control center.

For in-home energy management, the smart meter must be equipped with a 4G connect unit to communicate with the battery system. This enables Dynamic Load Balancing (DLB), a feature that prevents overloads on the household's main fuse by dynamically adjusting the battery's power flows. For a proper installation a modern distribution board, adequate ventilation, and a thermally stable environment is required to ensure that the battery can optimally perform. To utilize the full capacity of the 20 kWh / 10 kW variant, a three-phase grid connection is required. A typical 3×25 A connection permits up to 17.25 kW of simultaneous power usage. Since the inverter alone can draw or supply up to 10 kW, Dynamic Load Balancing ensures that the system will not exceed the connection's maximum capacity during periods of high household consumption.

Figure 11: Technical components Zonneplan Nexus home battery system

4.2.2 Battery control system

Figure 12 provides a schematic overview of how Zonneplan optimizes the control of its home battery systems based on imbalance prices. In other words, it illustrates the passive balancing strategy currently applied by Zonneplan. While the approach is tailored to Zonneplan's operational setup, it is assumed that competing aggregators follow a largely similar strategy.

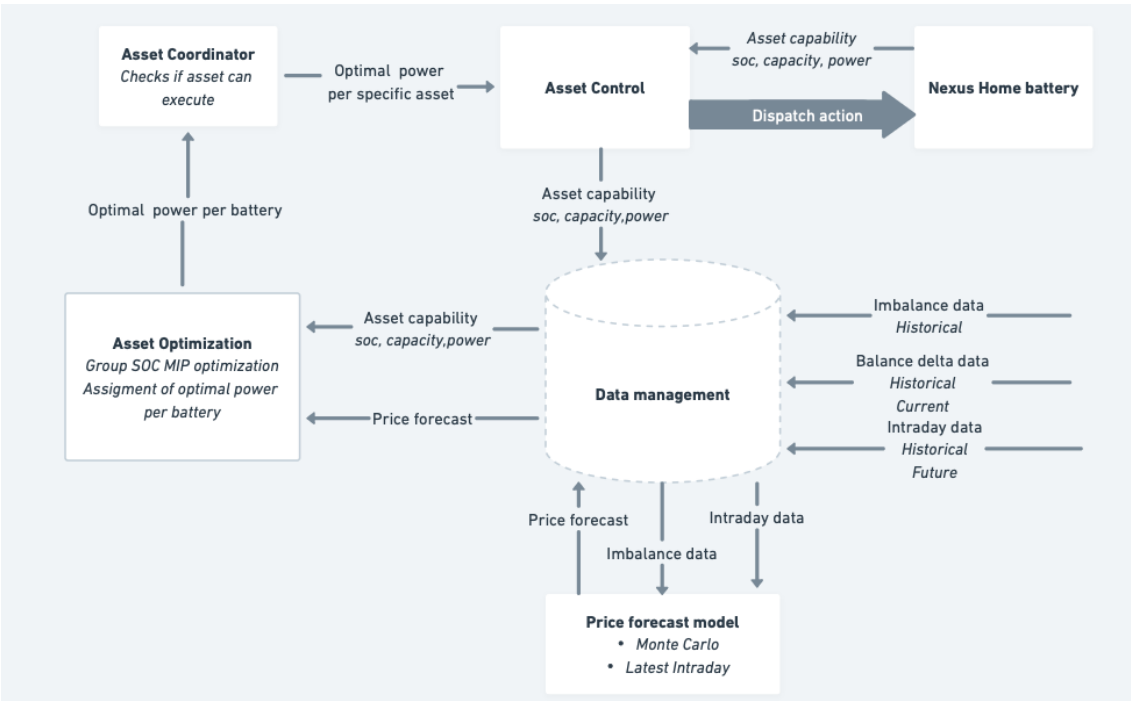


Figure 12: High Level System Design passive balancing optimization approach

The process can be divided into several key components, each of which is briefly described below.

1. Price Forecast model
Every minute, a forecast is generated for the imbalance price of the current Imbalance Settlement Period (ISP). Since the start of Zonneplan's passive balancing operations, various forecasting models have been used. The data used for the performance analysis of passive balancing later in this chapter, is based on predictions from two different models, as no single model provides a full backcast over the entire period.

- From January to December 2024, a model was used that forecasts the current ISPs imbalance settlement prices (Price shortage and Price Surplus) based on the real-time available minute-level imbalance prices within the respective ISP.
- From January to March 2025, a Monte Carlo-based price forecasting model was applied. This model generates a probabilistic forecast of all possible activated aFRR volumes per minute and their likelihood. Based on the imbalance price mechanism, which includes the regulation state determination rules, it estimates both the imbalance Price Shortage and Price Surplus levels.

In addition to the real-time imbalance price forecast, every minute a 12-hour price forecast is produced using the latest available Intraday prices per quarter-hour. This longer-term forecast is important for valuing current prices relative to expected future prices.

2. Asset Optimization
The price forecast serves together with the asset capabilities as the main input for Asset Optimization. Within Asset Optimization a Mixed Integer Programming (MIP) solver is used to determine the optimal power per minute for each battery. In the first step of the optimization the price forecast is used to generate the optimal power for 11 different State-of-Charge (SoC) groups and all feasible combinations of maximum (dis)charging power per ISP. In the next step, the solver optimally assigns the optimal power output per SoC group to specific batteries matching the current capabilities of the battery. Multiple key parameters are used in the optimization from which the minimum required margin (spread) between charge and discharge price is the most important one to consider.

3. Asset Coordination
The desired optimal power per minute per battery and the real-time capabilities of individual batteries is passed to the Asset Coordinator. The Asset Coordinator verifies whether the batteries are capable of executing the optimal power assigned by Asset Optimization. No further optimization is performed at this stage, only verification.

4. Asset Control
The optimal power per battery is sent to Asset Control, where it is translated into control signals for each battery. These signals initiate the actual dispatch actions. As noted earlier, the batteries continuously report their available capacity and operational status back to Asset Control.

5. Data Management
The final component in the system architecture is Data Management. This system handles the collection of all necessary market data, logs the outputs of the various process stages, and provides required data access for analysis and system operation.

4.3 Regulation state distribution

Figure 13 shows the distribution of regulation states for the full years 2022 to 2024, as well as for the first five months of 2025. The Figure clearly illustrates a sharp increase in the frequency of RS2 quarters in 2024, a trend that appears to continue into 2025. *Figure 43* (Appendix C) presents the monthly frequency of Regulation State 2 from January 2024 to May 2025, revealing a consistent month-by-month increase, aside from two short-term dips.

It is important to note that the increase in the frequency of RS2 appears to be largely driven by the disappearance of RS0. This suggests that quarters which previously required no regulation volume are increasingly turning into periods in which both upward and downward aFRR capacity is activated.

In the following section, the impact of these developments on the revenue performance of the passive balancing strategy is further evaluated.

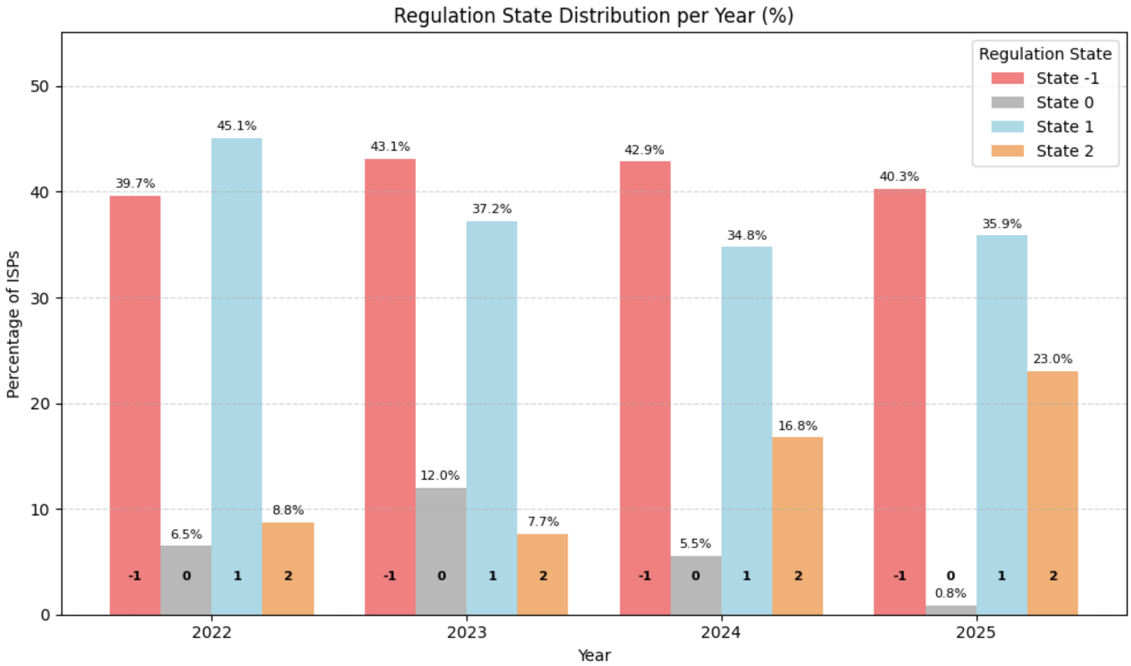


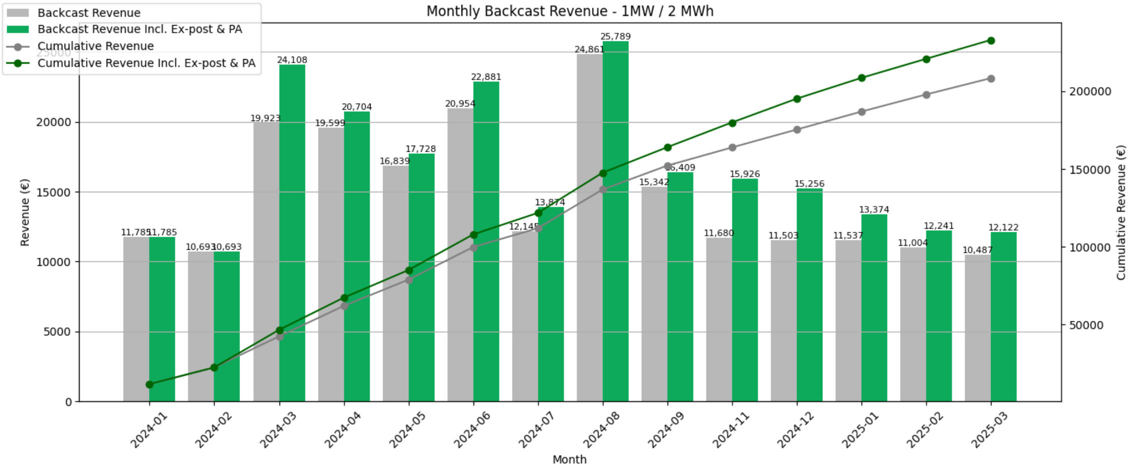
Figure 13: Regulation state distribution (%) by Year 2022-2025

4.4 Passive balancing backcast results

This section presents the results of the passive balancing backcast, which will later be compared with the outcomes of the aFRR bidding simulations in Chapter 6.

4.4.1 Revenue per month

Figure 14 presents a side-by-side comparison of the backcast revenue for batteries, both excluding and including Ex-Post trades and portfolio advantages. Several patterns are noteworthy. First, revenues were relatively low in January and February 2024, followed by a sharp increase beginning in March. Second, July 2024 exhibits a notable dip in revenue, despite high revenues in both the preceding and subsequent month. Third, from September onward, revenue appears to decline gradually and consistently. Lastly, while Ex-Post trades and portfolio effects consistently enhance revenues across the entire period, the magnitude of this improvement varies considerably from month to month. Contrastingly to expected based on the trends in RS2, the difference tends to decrease near the end of the backcasted period.



In January and February 2024, the results with and without ex-post trades and portfolio advantages are identical, as Zonneplan only began Ex-Post trading in March. These months should therefore be disregarded in the side-by-side comparison.

Figure 14: Monthly Passive balancing Revenue 1 MW / 2 MWh – Excl. vs Incl. Ex-Post trading and internal and external portfolio advantages (Jan 2024 – March 2025)

4.4.2 Monthly charged and discharged volumes by regulation state

Figure 15 displays monthly charge and discharge volumes, categorized by regulation state. These volumes represent the net positions settled per 15-minute Imbalance Settlement Period (ISP). They are notably lower than the total physical charging and discharging volumes, revealing an inefficiency inherent to passive balancing. As shown in Table 18 (Appendix C), approximately 13% of the total energy delivered is lost due to simultaneous charging and discharging within the same ISP, volume that is not recognized in settlement.

The total settled volumes vary significantly by month. In general, months with higher volumes tend to correspond with higher revenues. For example, January and February 2024 recorded low volumes and correspondingly low revenues. August 2024 had both high volume and high revenue. However, this pattern is not consistent across all months. In March 2024, high revenue was achieved despite relatively modest volumes, whereas December 2024, the month with the highest volume, did in comparison not yield high revenue. This discrepancy can be attributed to the fact that a substantial share of the energy in December was charged and discharged during Regulation State 2. Although ex-post trades and portfolio advantages yielded a slightly positive result during this State, their contribution to total revenue was limited.

A particularly notable observation is that charging and discharging occurred in all Regulation States (1, -1, and 2) throughout nearly every month. Ideally, discharging should occur during RS1, and charging during RS-1, as these actions support system balance. Imbalance pricing is designed to incentivize such behavior. The deviation from this expected pattern suggests suboptimal activation under passive control. Several factors may explain this behavior:

- During RS 1, the price shortage and price surplus are equal and may still be relatively cheap to charge. While this typically does not offer strong incentives to charge and it's very risky, it may become attractive if a high price is expected in the next ISP. The willingness to pay for energy is then influenced by the anticipated selling price.

- During RS-1, discharging often results in a cost, but may still occur if a significant negative price shortage is expected in the following ISP. Reducing the state of charge in advance allows for deeper charging when prices become highly favorable.
- The price forecast may have indicated high or low imbalance prices, resulting in premature discharging or charging. This behavior is especially common at the beginning of an ISP, when the final regulation state and associated price shortage or surplus are still highly uncertain. Because of the balance delta publication delay, the forecast in the first five minutes is based only on historical data and projected trends, without access to real-time price signals from the current ISP, thereby increasing the risk of early suboptimal activation.

Despite the disincentivizing nature of dual pricing during RS2, considerable volumes are still charged and discharged during these ISPs. This can be partially explained by the fact that the regulation state is only determined at the end of the ISP. As a result, charging or discharging may occur early in the period based on initially favorable price forecasts.

Finally, consistent with the regulation state statistics presented in *Figure 13,* which show that Regulation State 0 is now nearly absent, the volume of charging and discharging under this State is negligible (see *Figure 15)*. It is also evident that the increase in RS 2 state 2 ISPs has not led to a proportional increase in activated volumes during RS2. In 2025, lower monthly volumes during RS2 are observed which could be due to the use of the improved Monte Carlo price forecasting model. This partly explains why the difference in the revenue comparison in *Figure 14* during these months was lower. Additionally, as shown in Table 18 (Appendix C), the simultaneous charge and discharge activity within a single ISP also appears to be lower during these months, suggesting more effective control on this part. *Figure 42* in Appendix C shows the monthly discharged and charged volumes by regulation state including unsettled volume.

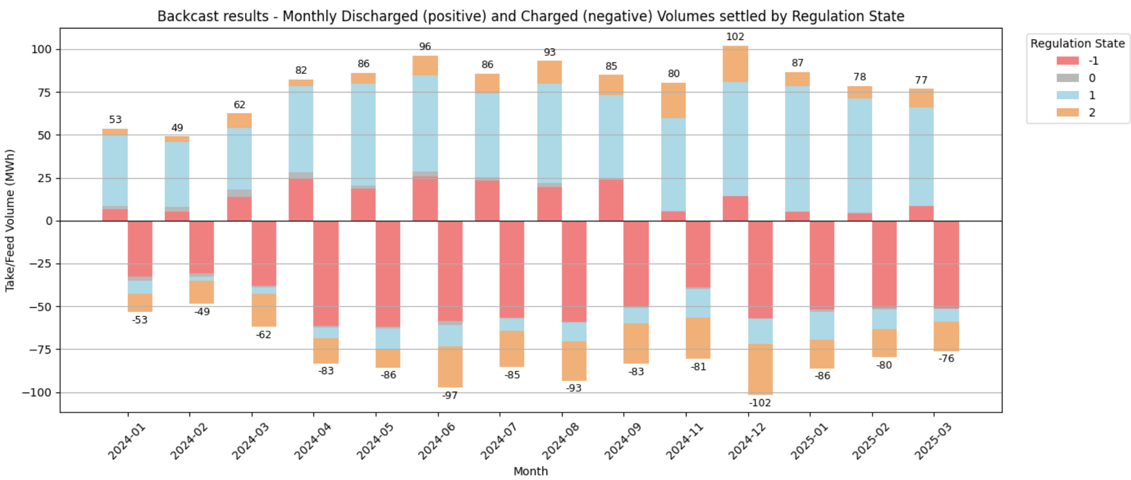


Figure 15: Monthly passive balancing Discharged (positive) and Charged (negative) settled Volumes by regulation state (Jan 2024 – March 2025)

4.4.3 Monthly revenue by regulation state

Figure 16 shows the distribution of revenue (Including Ex-Post and PA) across regulation states in which three things stand out:

- On average, most charging occurs during RS-1, as also shown in the previous Figure. As a result, revenue during RS -1 mainly reflects the value of charging. A clear trend is visible: at the beginning of the period, charging was often compensated, meaning batteries were paid to charge. Over time, this shifted toward neutral or even negative values, indicating that charging increasingly came at a cost.

- RS1 is the main contributor to total revenue. This underscores the importance of discharging during ISPs in which the system is short. Being able to time discharging effectively during RS 1 appears to be the more critical to overall performance than forecasting the ideal moment or price for charging.
- Although RS2 ISPs do not appear to significantly reduce total revenue under current conditions, they also do not contribute meaningfully.

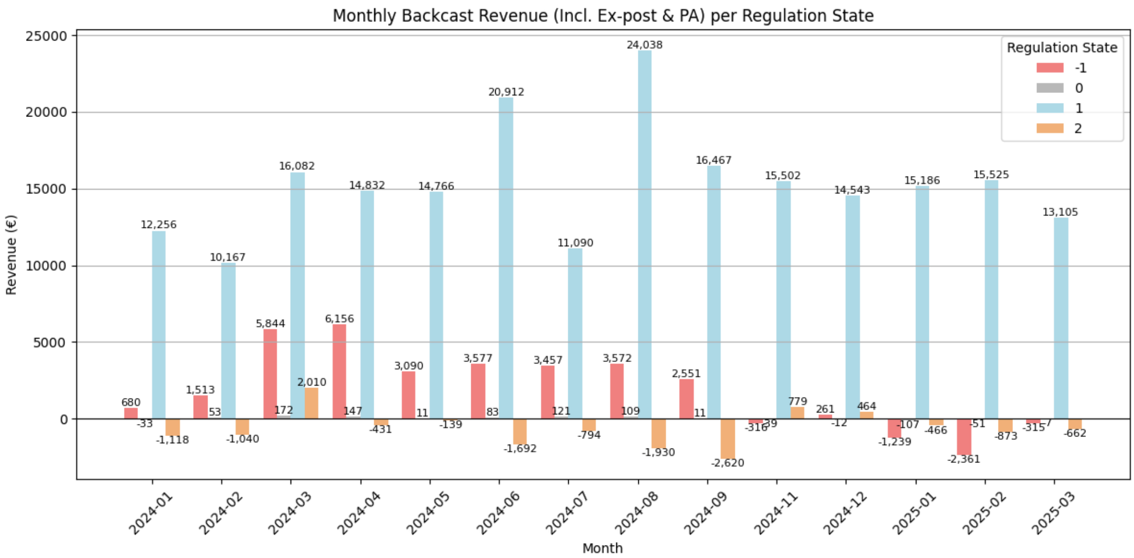


Figure 16: Monthly passive balancing Revenue (incl. Ex-post & PA) by regulation state (Jan 2024 – March 2025)

4.4.4 Volume-Weighted average charge and discharge prices

Figure 17 shows the volume-weighted average charge and discharge prices per month. For discharge prices, or price surplus, the average monthly value closely aligns with the pattern in overall revenue, which is to be expected. More importantly, a clear trend emerges in the average charge price. As suspected, based on the revenue per RS shown in *Figure 16*, the price for charging shifts over time from negative to positive. This suggests that in the later months of the period, charging leads to a cost instead of a gain.

It is important to note that the average prices shown are heavily influenced by whether the batteries are able to capture extreme price spikes. Figures 43-46 in Appendix C illustrate the dynamics of these price peaks. Since the marginal aFRR price dispatch up and down during Regulation States 1 and -1 directly determines the price surplus (discharge price) and price shortage (charge price) (unless mFRR is activated), this topic will be explored further in the aFRR market analysis.

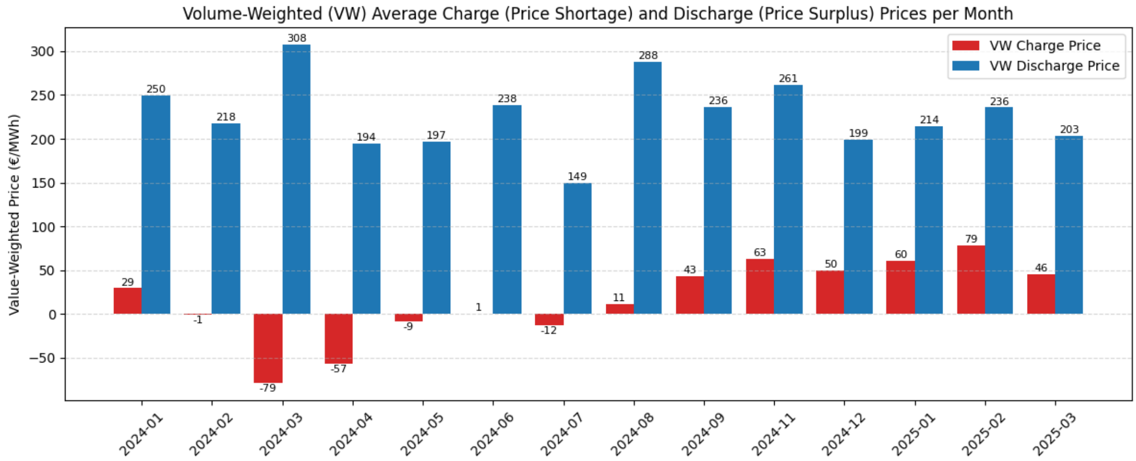


Figure 17: Monthly passive balancing Volume-Weighted Average Prices for Charging and Discharging (Jan 2024 – March 2025)

4.5 Conclusion

SQ1: How does the currently used passive balancing strategy of Zonneplan work and how does it perform under the growing frequency of Regulation State 2 ISPs

Zonneplan's passive balancing strategy, which involves taking strategic out-of-balance positions based on imbalance price forecasts, initially showed increasing revenue, peaking in August 2024, but consistently declined thereafter. This decline was primarily due to lower activated volumes and rising charging costs. A critical finding was the increasing frequency of Regulation State 2 (RS2) Imbalance Settlement Periods (ISPs). While Ex-Post trading and portfolio advantages largely offset the financial risk of RS2, these periods contributed minimally to overall revenue, suggesting that the growing prevalence of RS2 may be limiting volume opportunities for passive balancing. The inherent inefficiency of passive balancing, with approximately 13% of energy lost due to simultaneous charging and discharging not recognized in settlement, and suboptimal activation patterns, further highlighted its limitations.

5 aFRR Market Analysis

This chapter presents an analysis of the aFRR market. First an example of a typical bid price ladder and the evolution of the bid price ladder over time is discussed. Then statistics of the contracted capacity are presented and analyzed. Next, the activated energy bids are analyzed more elaborately, discussing the activated volume, upward and downward activation prices. The analysis includes comparison of the last years since 2021 but focuses on 2024-2025. It is important to note that, although this market is highly dynamic and influenced by numerous factors, year-over-year and month-over-month comparisons are not always meaningful. However, discussing and analyzing the market data does help to gain an understanding of the market potential, size and the direction of trends. This chapter addresses Sub-Question 2 and provides relevant insights for the aFRR bidding strategies simulated in the following chapter.

5.1 Bidding ladder

As discussed in Chapter 2, TenneT procures both upward and downward aFRR capacity through a daily tender. The awarded BSPs are obligated to submit energy bids ahead of a fixed deadline. These bids are published on the live bidding ladder on TenneT’s website. Bids may be updated until 25 minutes before the delivery period. In addition to these contracted bids, so-called “free bids” are submitted voluntarily and are subject to the same update deadline. As noted earlier, contracted capacity is predominantly provided by gas-fired power plants, which are currently required to offer continuous availability over 24 hours, a requirement that is expected to be reduced to 4 hours by the end of 2025. Free bids are assumed to originate from an already more diverse mix of assets, particularly for downward capacity.

All energy bids are placed on a common bidding ladder: upward bids are sorted from low to high price (with cumulative capacity or capacity threshold), and downward bids from high to low price. The publicly available data from TenneT is aggregated in 10 MW steps and does not show individual bids, but it provides a clear approximation of how much volume must be activated to reach a given price level.

Examining the bidding ladder of a single Imbalance Settlement Period (ISP), as shown in *Figure 18* reveals valuable patterns useful for developing bidding strategies. Even though there is considerable variation in the volume and shape of the bidding ladder across ISPs, a number of consistent bidding patterns can be identified. For upward capacity, most bids are clustered at relatively low prices (typically below €200/MWh), with a sharp price increase at the end of the ladder, often reaching a maximum price of €1,895 in just a few steps. A similar, though not identical, pattern is observed for downward capacity. The downward ladder generally includes more volume, and while prices remain low for the first portion, they begin to increase more gradually, sometimes in smaller price steps. Compared to upward bids, there appears to be greater downward capacity at low bid prices. This likely reflects higher competition or overcapacity in downward regulation, encouraging BSPs to bid closer to marginal costs.

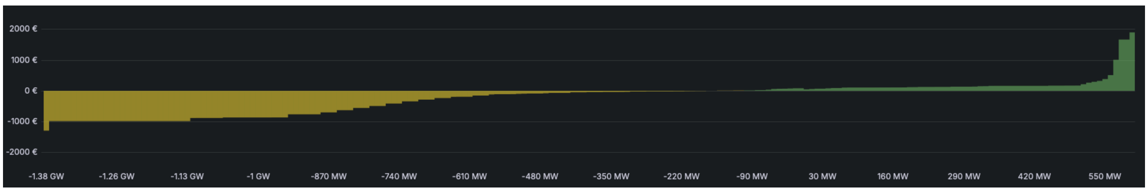


Figure 18: Example Bidding ladder of a single ISP 2025 – Downward bids (yellow) and upward bids (green)

Comparing bidding ladders across days or ISPs is challenging due to high variability driven by weather and other market factors. But while presenting consistent daily statistics is difficult, it remains informative to explore high-level trends. Therefore *Figure 19* and *Figure 20* are used to illustrate the evolution of maximum upward prices, minimum downward prices, and the associated maximum/minimum capacities over 2024 and early 2025.

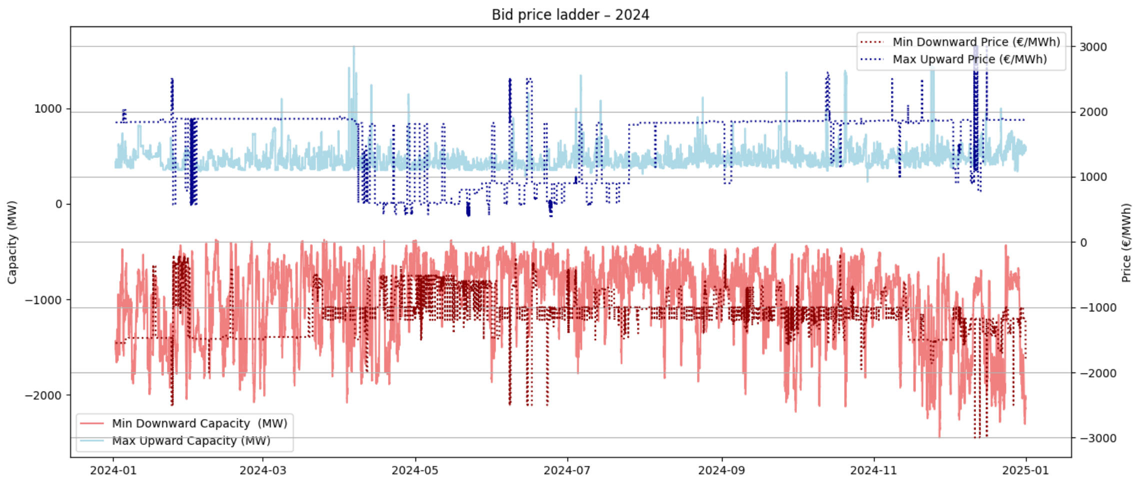


Figure 19: Bid Price Ladder 2024 - Minimum and Maximum capacity and prices

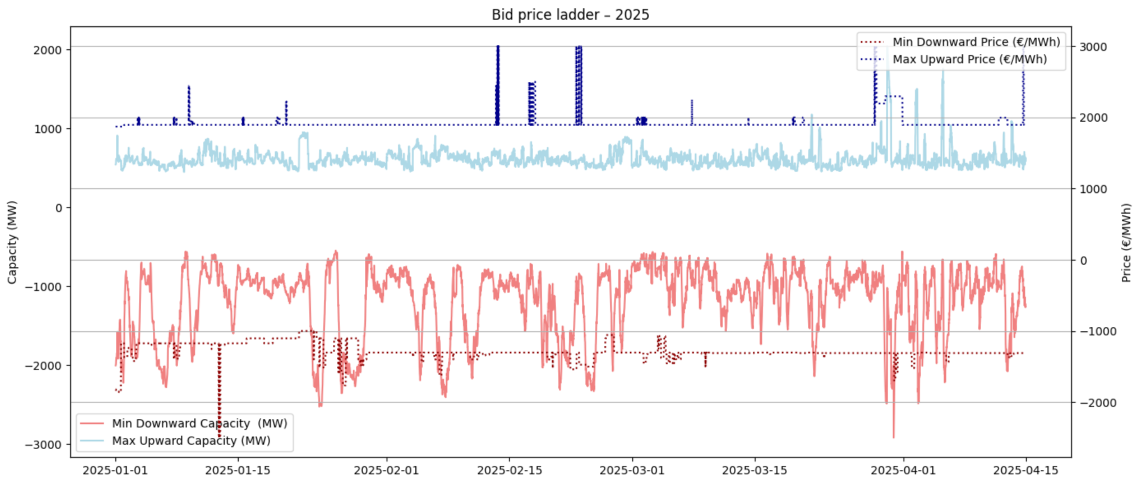


Figure 20: Bid Price Ladder 2025 – Minimum and Maximum capacity and prices

Analyzing the two Figures above, two observations stand out:

Price Stability: The maximum and minimum bid prices in the ladder showed significant volatility in 2024 but have stabilized notably in 2025. Although the cause is uncertain, it appears that one or multiple BSP's now consistently submit a maximum bid at € 1,885. In cases of full activation, this bid sets the ISP dispatch up price. While this value still showed some variation in 2024, it has remained consistently at a minimum of € 1,885 since the beginning of 2025, with only a few occasional upward peaks.

Capacity Variability: There is considerable variation in available capacity, with greater volatility on the downward side. This could be explained by the fact that wind and solar generators can offer downward regulation by curtailing production, an option highly dependent on weather conditions. The agricultural sector may also contribute more to downward capacity when flexible consumption is available. In contrast, gas plants can only offer downward regulation if already generating. Upward capacity is more stable, being tied primarily to gas units that can only ramp up if active and not already running at full capacity.

5.2 Contracted capacity

Table 5 shows the average contracted upward and downward capacity and prices, including standard deviations. As also noted in [3], we see very high prices for both upward and downward capacity in 2022 which reflects the high gas prices during the 2022 gas crisis. Additionally, the peak in standard deviation reflects the high volatility in 2022. Since 2023 we see a steady decrease in both upward and downward contracted capacity fees. This could indicate that a growing supply of flexible resources is increasing competition, driving prices down or could be the result of stabilizing gas prices. When the capacity market will change from 24 hours to 4-hour blocks, competition is going to increase even further, and capacity price could go down even more. Potential revenues from the capacity market are disregarded for the bidding strategies simulated in this research.

Average contracted upward capacity has been rising steadily in time. This is as expected as the minimum required contracted capacity level has increased as well. The average is just above the minimum level discussed in Chapter 2, which is consistent with expectations. For Downward capacity we see slightly higher values, but the same increase in accordance with required minimum levels. Although the 2025 values represent only the first four months and are not directly comparable to full-year figures, they still indicate a comparable upward trend.

Table 5: Contracted Capacity – Price and capacity statistics based on [3], [46]

Year	Average contracted upward capacity	Standard deviation in the volume of contracted upward capacity	Average price of contracted upward capacity	Standard deviation in the price of contracted upward capacity	Average contracted downward capacity	Standard deviation in the volume of contracted downward capacity	Average price of contracted downward capacity	Standard deviation in the price of contracted downward capacity
	(MW/day)	(MW/day)	(€/MWh)	(€/MWh)	(MW/day)	(MW/day)	(€/MWh)	(€/MWh)
2021	331	63	29	25	393	119	22	30
2022	332	36	106	98	373	92	89	108
2023	341	38	44	22	399	88	31	29
2024	388	58	33	15	425	105	21	21
2025*	500	64	30	11	534	57	12	10

** Until May 2025*

5.3 Activated energy bids

Table 6 shows the total activated upward and downward volumes and prices, including the standard deviation in price.

Looking at the volumes we see a peak in activation in 2022, which again can be contributed to the chaos caused by the gas crisis. In 2023 we see that both upward and downward activation dropped again, even lower than in 2021. In 2024, volumes increased once more, with a noticeable acceleration following the introduction of PICASSO. For meaningful comparison, the statistics include the January-May activation volumes and prices in 2024 (pre-PICASSO) and 2025 (post

PICASSO). The Dutch aFRR prices are relatively low compared to other PICASSO countries, which could be the reason for more activation. Secondly, the higher frequency of Regulation State 2 and constant overshoots seems to lead to more activation too. The near disappearance of ISPs in Regulation State 0, where no upward or downward regulation occurs, suggests that activation is occurring more frequently.

Prices also peaked in 2022, but unlike volumes, they have continued to decline since then. This could be the effect of stabilizing gas prices but could also indicate increased competition pushing prices down. However, it's hard to fully capture what's happening based on average prices, while this doesn't show if the mix of high and low prices is changing. The standard deviation for upward regulation peaked in 2024, but seems to be decreasing again in 2025, also when only comparing the first 5 months. This indicates that, in addition to falling prices, volatility is also decreasing. For downward regulation prices we see the standard deviation peak in 2022 but also see a peak in 2024. In 2025 the standard deviation seems to decline again, but contrastingly to upward prices, we see an increase in average downward regulation prices. Note here that a positive downward regulation price means that the BSP pays TenneT to activate downward capacity. An increasing price thus means that BSP's on average are paying more to TenneT. This is not in line with the expected result of more activation, caused either by PICASSO or Regulation State 2, that could potentially lower downward prices.

Table 6: Activated Energy Bids – Volume and price statistics based on data from [49]

Year	Total activated upward volume	Average price of activated upward capacity	Standard deviation in price of activated upward capacity	Total activated downward volume	Average price of activated downward capacity	Standard deviation in price of activated downward capacity
	(GWh)	(€/MWh)	(€/MWh)	(GWh)	(€/MWh)	(€/MWh)
2021	272	174	151	334	40**	87
2022	408	361	221	360	105	168
2023	246	186	246	259	19	105
2024	325	169	294	374	1	129
2024*	107	150	291	144	-4	134
2025*	231	152	219	209	32	92

**Period January to May only*
***Note that a positive price for activated downward capacity means that the BSP pays TenneT*

5.3.1 Price dispatch up & down duration curves (Jan-May 2024/2025)

To provide a clearer understanding of the duration over which different price levels occur, the following price duration curves are presented for both upward and downward aFRR prices. *Figure* 21 compares 2023 with 2024, and *Figure* 22 2024 and 2025. The curves are based solely on data from January to May to identify trends in the latest available period.

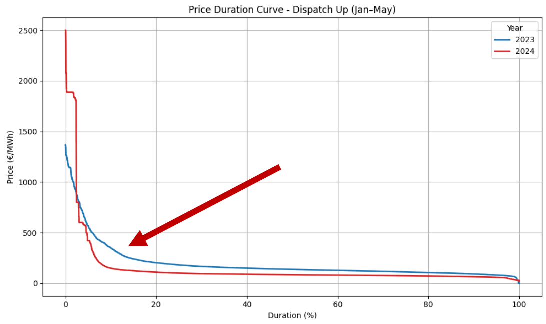


Figure 21: Price Duration Curve Dispatch Up (Jan-May) 2023 vs. 2024

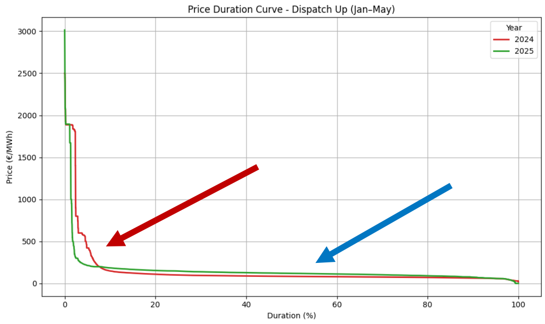


Figure 22: Price Duration Curve Dispatch Up (Jan-May) 2024 vs. 2025

In the comparison of the upward price duration curves of 2023 and 2024 it stands out that in 2024 the maximum price was much higher. Additionally, much more extreme price peaks are observed in 2024 at a constant level of around € 1,900 and around € 600, while in 2023 we see a much smoother distribution of prices. Also, in 2023 the average price seems to be higher most of the time. The duration of prices between the extreme peaks and the more typical price levels has declined consistently since 2023, as indicated with the red arrows. Compared to 2024, the frequency of extreme price peaks appears to be decreasing in 2025, while the average price during most periods is slightly higher as indicated with the blue arrow.

For the downward prices in *Figure* 23 and *Figure* 24 we see the same trend for extreme low-price peaks. They occur less frequently. Also, similar as for upward, the duration of time of prices between peak levels and average levels is declining, as indicated with the red arrow. However, contrastingly to upward prices, the downward prices are most of the time higher in 2025 than in 2024, as indicated with the blue arrow, meaning that most of the time BSP's are paying more to TenneT as also observed in the average prices as discussed above.

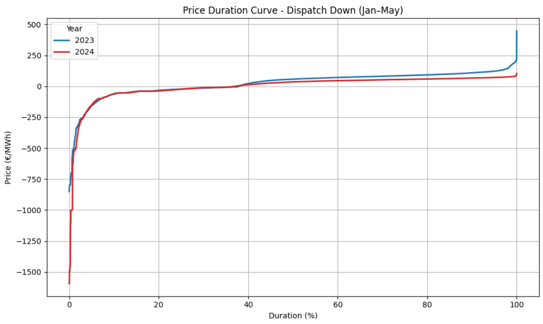


Figure 23: Price Duration Curve Dispatch Down (Jan-May) 2023 vs. 2024.

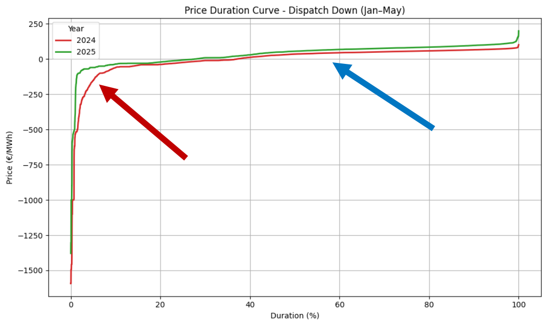


Figure 24: Price Duration Curve Dispatch Down (Jan-Mar) 2024 vs. 2025

In conclusion, for upward prices, there is a trend toward fewer price peaks but higher prices during most periods. Similarly, for downward prices, we observe fewer extreme price dips and generally higher prices. Unlike the upward prices, this means BSP's pay more when activated rather than receiving higher compensation.

5.3.2 Average price dispatch up & down per ISP (2024)

The price duration curves give a good sense of the distribution of prices across a longer period, but don't show daily dynamics. As is well known from Day-Ahead prices, there is a pronounced daily pattern in prices. This dynamic is also important to consider when evaluating the potential of aFRR and developing bidding strategies. Therefore, *Figure* 25 presents the average upward dispatch price for each quarter-hour (ISP) throughout the day in 2024.

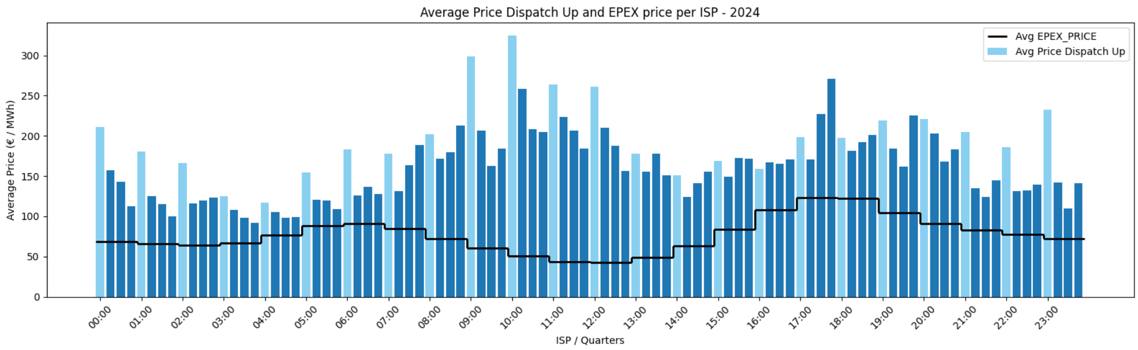


Figure 25: Average Price Dispatch Up and EPEX price per ISP – 2024

Similarly, as discussed in Chapter 4, where we saw that there is a higher frequency of Regulation State 2 in the first ISP of an hour, we see that during the first quarter the price Dispatch Up is much higher in almost every hour, as indicated with light blue. This could be for similar reasons as for the higher frequency in RS 2. Only from 13.00 and 20.00 the price of first quarter hour is not higher. During the day we see a similar sequence as in DAM prices but slightly shifted to the right. Prices are on average higher during the beginning and end of the day and are lower during the middle of the day and at night. Notably however, during the night the difference in price during the first ISP of an hour end the remaining ISPs is the highest. This Figure also clearly illustrates how on average the aFRR upward prices are much higher than prices on the DAM, making it a very attractive market to participate in.

Figure 26 then presents the Average Price Dispatch Down for each ISP of the day in 2024. In contrast to the Price Dispatch Up there is not a very strong pattern across first ISP of hours, except for almost exactly the period where the pattern is less strong for Price Dispatch Up: From 13.00 to 21.00 we see clearly lower prices in the first ISP of an hour, meaning BSPs get compensated more for delivering downward capacity during these quarters. The delta between DAM prices within this price range is also higher, suggesting that the fuel mix changes more. Intuitively it also makes sense that during the beginning of the hours where gas plants adjust their output upwards for their scheduled hour position, it is more expensive to ramp down at the same time. Also, possible available downward regulation volume is lower during these quarters.

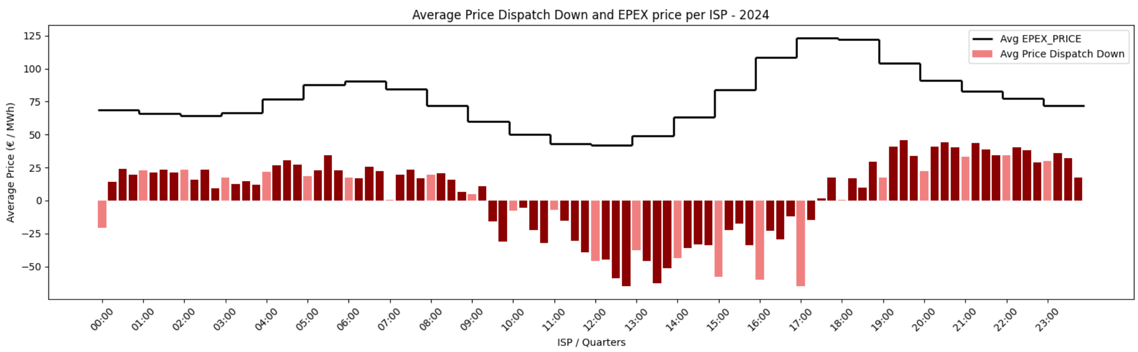


Figure 26: Average Price Dispatch Down and EPEX price per ISP – 2024

The same reasoning holds for upward regulation where we see that when DAM prices are decreasing and gas plants ram down, activation in opposite direction is more expensive. The most important take-away for downward prices is that during the middle of the day prices are generally below 0, meaning that you receive money for delivering downward volume. Furthermore, compared to downward prices, the DAM prices are consistently higher throughout the entire day. This means that if offering downward capacity by charging batteries is always much cheaper by charging through downward activation then by charging for the DAM price and in the middle of the day, it is even possible to earn money by charging instead of receiving money. Lastly, the following pattern is overserved: after high activation prices for upward there is a period of low activation for downward followed again with a period with high price for upward.

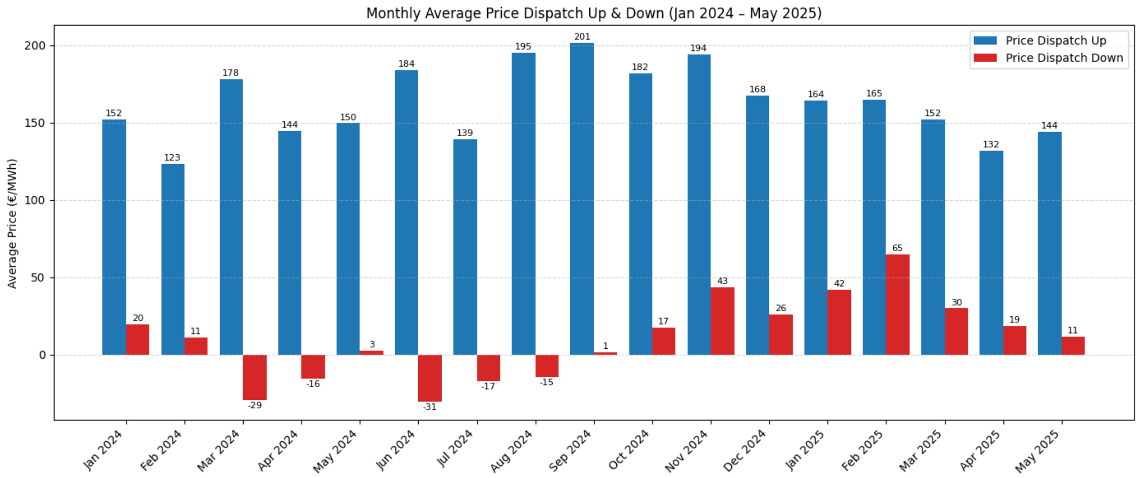


Figure 27: Monthly Average Price Dispatch Up & Down (Jan 2024 - May 2025)

5.3.3 Price dispatch up & down peaks

Figure 28 shows the evolution of upward and downward ISP prices during March 2025. It's visualizing the two most important dynamics. Firstly, it shows the extreme price peaks for both upward and downward regulation are respectively higher and lower compared to most common prices. Secondly, it shows that often periods of upward activation alternate with periods of downward activation. Similarly, as for passive balancing, the performance of aFRR bidding strategies will be highly dependent on capturing these price peaks and maximizing activated volumes during these peaks. The alternating pattern between upward and downward activation automatically helps to keep the State of Charge (SoC) in a useful range as charging and discharging alternates if activation takes place in both directions after each other. However, during certain periods, high prices may be absent for extended durations, or prolonged upward or downward regulation may occur. This can lead to situations where batteries are unable to offer capacity because they become fully charged during extended downward regulation or completely depleted during extended upward regulation.

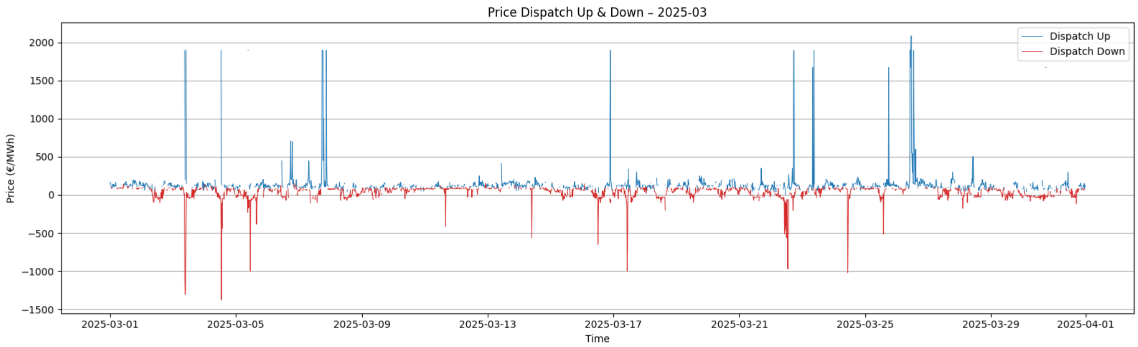


Figure 28: ISP Price Dispatch Up & Down – March 2024

Finally, as learned from the passive balancing analysis in Chapter 4, there is a growing frequency of RS 2 ISPs which for the passive balancing strategies mainly forms a problem during the high price peaks. For aFRR activations RS 2 price risk doesn't exist because the delivered volume is always settled with the highest upward or lowest downward activations price within the respective ISP. Table 7 below shows a considerable amount of upward price peaks occurred during RS 2 in 2024. For downward peaks we even see that, especially for the extreme low peaks, almost just as many peaks occur during RS 2 as during RS -1. A difference in performance between passive balancing and aFRR is therefore expected to be largely influenced by the fact that with aFRR you can profit from more price peaks.

Table 7: Frequency of upward and downward ISPs by price range and regulation state (2024)

Price Dispatch Up 2024				**Price Dispatch Down 2024**			
Regulation State	**-1**	**1**	**2**	**Regulation State**	**-1**	**1**	**2**
≤200	1315	10813	5509	≤-1000	80	3	80
200 – 400	12	556	140	-1000 – -800	5	0	4
400 – 600	9	303	57	-800 – -600	24	0	25
600 – 800	6	96	20	-600 – -400	63	1	81
800 – 1000	3	123	30	-400 – -200	164	4	213
1000 – 1500	1	26	15	-200 – 0	5434	318	2528
>1500	21	309	123	0 – 200>	9246	260	923

5.4 Conclusion

SQ2: What are the current trends in the aFRR bidding ladder, prices and volumes?

The analysis of the Dutch aFRR market reveals several important trends. The bidding ladder shows consistently high prices for upward regulation, with sharp increases at higher volumes, while the downward bidding ladder is more volatile, featuring fluctuating minimum prices and greater capacity at low bids, reflecting stronger competition. Since 2022, contracted capacity prices have generally declined due to stabilizing gas markets and more flexible capacity entering the market, while activated volumes have grown, especially after PICASSO's introduction in late 2024. PICASSO has reduced extreme upward price peaks but led to higher average prices, flattening the price curve with more frequent moderate activations. For downward prices, fewer extreme dips occur, and overall prices are higher, meaning BSPs pay more to provide downward capacity. Crucially, the market displays a clear alternating pattern: aFRR upward prices are consistently higher at the beginning and end of the day, making discharge attractive, while frequent negative Downward prices around midday enable profitable charging. This natural cycle of high upward and low downward prices supports battery state-of-charge balancing and makes active participation in aFRR particularly attractive. Furthermore, many price peaks occur during Regulation State 2, offering a structural advantage for active aFRR strategies, as they receive full remuneration, unlike passive balancing.

6 aFRR bid Simulation Results

This chapter presents the results of the bidding simulations. First the key results are presented for each bid strategy separately, with a short explanation of how these results were obtained and what stood out during the simulation of each bid strategy. Then, yearly results are presented side by side and Bid Strategy 2 is selected as most optimal bid strategy based on Net Revenue. Finally, the passive balancing backcast results are compared to the results of Bid Strategy 2, followed with a conclusion answering sub-questions 3.

6.1 Bid Strategy 1: aFRR constant bids

6.1.1 Bid Strategy 1a constant up 140 – down 90

The first tested Bid Strategy (1a) applies constant bid prices for both upward and downward aFRR bids, using a fixed spread of €50/MWh. This spread ensures that each charge-discharge cycle yields a net profit. The optimal combination of bid prices was determined by iterating over various bid price combinations, resulting in €140/MWh for upward bids and €90/MWh for downward bids. Both values are relatively high, particularly the upward bid price, which significantly influences the outcomes.

Upward activation volumes under this strategy are low, both in comparison to other strategies and to passive balancing results, indicating limited activation. The high upward bid price results in very high Volume-Weighted Average Prices (VWAP upward), showing that activation occurs mainly during extreme price peaks. Conversely, the high downward bid price ensures rapid recharging following upward activation. This leads to a VWAP Downward slightly above the average Dispatch Down prices as presented earlier in *Figure* 27. Only in March 2024 did downward activations yield net positive revenues, as reflected by a negative VWAP Downward. It is important to note that, in this simulation, the high downward bid price does not affect the final Dispatch Down price, under the assumption that the marginal bid would still have set the price, even though in practice the simulation bids could influence the merit order. See *Figure* 29 and *Table* 8.

This strategy highlighted that the upward bid price is the key determining factor, due to greater volatility in upward prices. As a result, the timing of downward activation (i.e., recharging) is largely dependent on prior upward activations. While this strategy results in low activation volumes but high spreads, the difference between (gross) revenue and net revenue (after accounting for degradation costs) remains small. This illustrates the trade-off between higher-volume strategies and degradation minimization. Although slightly more volume could increase net revenue, reduced cycling and thus lower degradation could be more profitable over the long term. However, this assumes that current market conditions and high spreads will persist, which cannot be guaranteed.

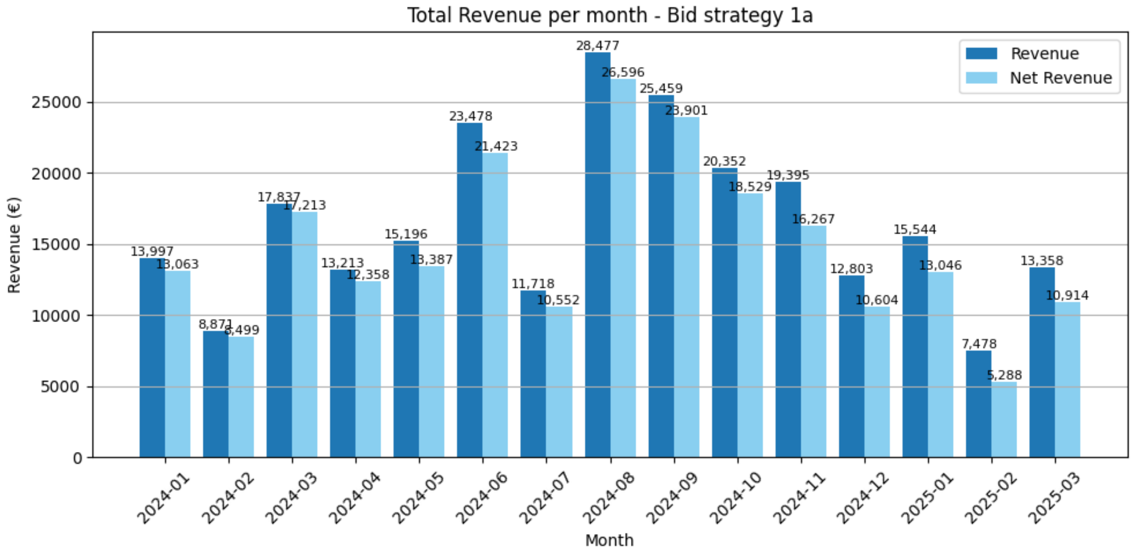


Figure 29: Total Revenue per month - Bid Strategy 1a (fixed minimum price spread of €50) with constant upward bids at €140 and downward bids at €90 (Jan 2024 – March 2025)

Table 8: Simulation results per month - Bid Strategy 1a (fixed minimum price spread of €50) with constant upward bids at €140 and downward bids at €90 (Jan 2024 – March 2025)

Month	Total revenue up (€)	Total revenue down (€)	Total revenue (€)	Total upward activations (volume)	Total downward activations (volume)	VWAP Up (€)	VWAP Down (€)	Degradation cost (€)	Net revenue (€)
01-2024	14325	-327	13997	17	21	858	16	935	13063
02-2024	8977	-106	8871	7	8	1317	13	371	8499
03-2024	17761	77	17837	12	13	1509	-6	625	17213
04-2024	13466	-253	13213	15	19	873	13	855	12358
05-2024	15995	-799	15196	33	39	481	20	1809	13387
06-2024	23744	-266	23478	38	44	629	6	2055	21423
07-2024	11877	-159	11718	21	25	553	6	1166	10552
08-2024	29016	-539	28477	35	41	841	13	1881	26596
09-2024	25519	-61	25459	29	34	887	2	1558	23901
10-2024	21499	-1147	20352	33	40	644	29	1823	18529
11-2024	21600	-2206	19395	58	67	374	33	3128	16267
12-2024	14368	-1565	12803	40	48	358	33	2199	10604
01-2025	16939	-1396	15544	47	53	362	26	2497	13046
02-2025	9528	-2050	7478	40	48	239	43	2190	5288
03-2025	15483	-2125	13358	45	53	348	40	2445	10914

6.1.2 Bid Strategy 1b constant up 100 – down 90

As a variation on the first strategy, Bid Strategy 1b removes the fixed minimum price spread constraint. Instead, the focus shifts to maximizing net revenue, regardless of the spread, by iterating over combinations of bid prices. The optimal configuration resulted in an upward bid price of €100/MWh and a downward bid price of €90/MWh. See *Figure* 30 and *Table* 9.

The lower upward bid price, compared to Bid Strategy 1a, leads to more frequent activation since this price level is reached more often. As a result, upward activation volumes increase and the VWAP upward decreases, although it remains relatively high. The average monthly spread between VWAP upward and VWAP downward exceeds €50/MWh in every month. It is important to note that this is based on monthly averages. Individual discharge and subsequent charge events may occur with smaller spreads, which can reduce profitability at the transaction level. Despite this, the strategy increases net revenue over the entire simulation period. However, the difference between gross revenue and net revenue also grows, indicating that while more activation leads to higher revenue, net revenue does not increase proportionally due to rising degradation costs.

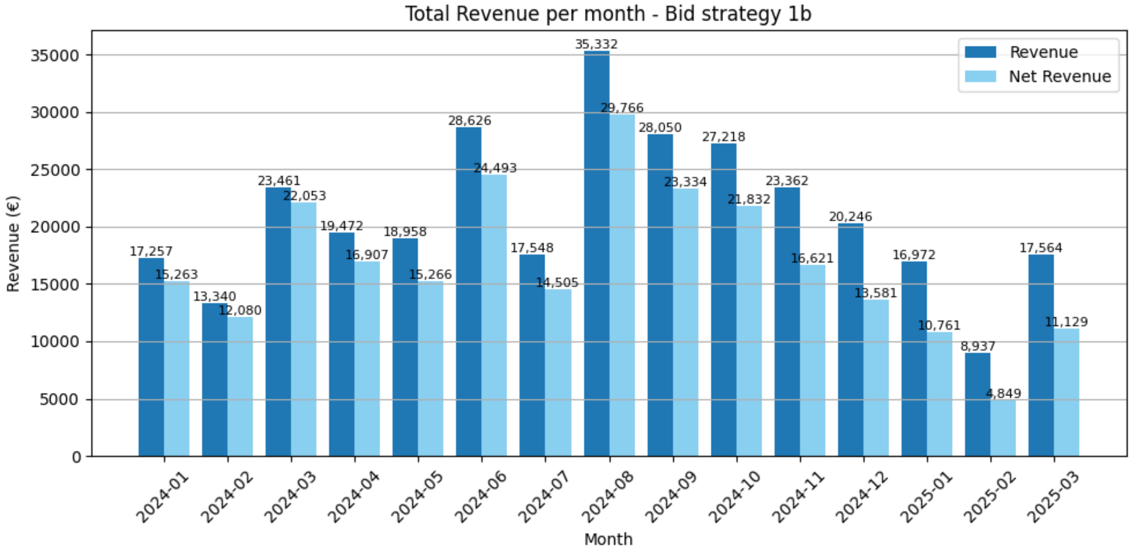


Figure 30: Total Revenue per month - Bid Strategy 1b with constant upward bids at €100 and downward bids at €90 (Jan 2024 – March 2025)

Table 9: Simulation results per month - Bid Strategy 1b (without minimum price spread) with constant upward bids at €140 and downward bids at €90 (Jan 2024 – March 2025)

Month	Total revenue up (€)	Total revenue down (€)	Total revenue (€)	Total upward activations (volume)	Total downward activations (volume)	VWAP Up (€)	VWAP Down (€)	Degradation cost (€)	Net revenue (€)
01-2024	18378	-1121	17257	36	44	508	26	1994	15263
02-2024	13176	164	13340	23	27	569	-6	1260	12080
03-2024	23326	134	23461	26	30	889	-4	1407	22053
04-2024	19911	-440	19472	47	56	426	8	2565	16907
05-2024	20656	-1698	18958	68	80	304	21	3691	15266
06-2024	28873	-247	28626	76	89	380	3	4133	24493
07-2024	17822	-274	17548	56	65	316	4	3042	14505
08-2024	36751	-1419	35332	102	121	361	12	5565	29766
09-2024	28825	-775	28050	87	102	331	8	4716	23334
10-2024	30209	-2991	27218	99	116	305	26	5387	21832
11-2024	27411	-4050	23362	124	145	221	28	6741	16621
12-2024	22104	-1858	20246	122	145	181	13	6665	13581
01-2025	19367	-2395	16972	115	134	169	18	6211	10761
02-2025	11605	-2668	8937	75	88	154	30	4088	4849
03-2025	21551	-3987	17564	118	139	183	29	6435	11129

6.2 Bid Strategy 2: Day-Ahead price based

Bid Strategy 2 builds on the results of Strategy 1 by aiming to further improve revenue and increase robustness. This was attempted by dynamically adjusting bids based on the day-ahead market (DAM) price. In this approach, the simulation iterated over combinations of constant upward and downward bid margins relative to the DAM price. The optimal combination was found to be an upward margin of +10 and a downward margin of +140, which resulted in the highest net revenue within the tested range. See *Figure 31*and *Table 10*.

Analysis of the top-performing combinations showed that most included an upward margin of +10 or were set close to or equal to the DAM price. The downward margin was consistently high, similar to the constant bidding strategies. This is noteworthy because the downward bid is added on top of DAM prices, which are already higher on average than the Dispatch Down prices. These high margins reflect the same limitations discussed earlier. A configuration with an upward margin of +10 and a downward margin of +20 resulted in only a small decrease in net revenue. This suggests that bidding extremely high does not significantly improve results, but neither does it severely reduce performance. The key insight remains that maintaining a high downward bid is beneficial, as it facilitates fast recharging after upward activation.

Compared to Strategy 1, this dynamic approach resulted in a clear improvement in revenue. The primary driver of this improvement is the increase in activated volumes, although in some cases the upward VWAP also improved. For example, in March 2025, activation volumes were nearly the same as in Strategy 1, but the upward VWAP was significantly higher. This indicates that dynamic bidding based on DAM prices not only increases activation but can also lead to better price capture. The price spread remains large enough to improve net revenue and, in some months, even results in more favorable VWAPs.

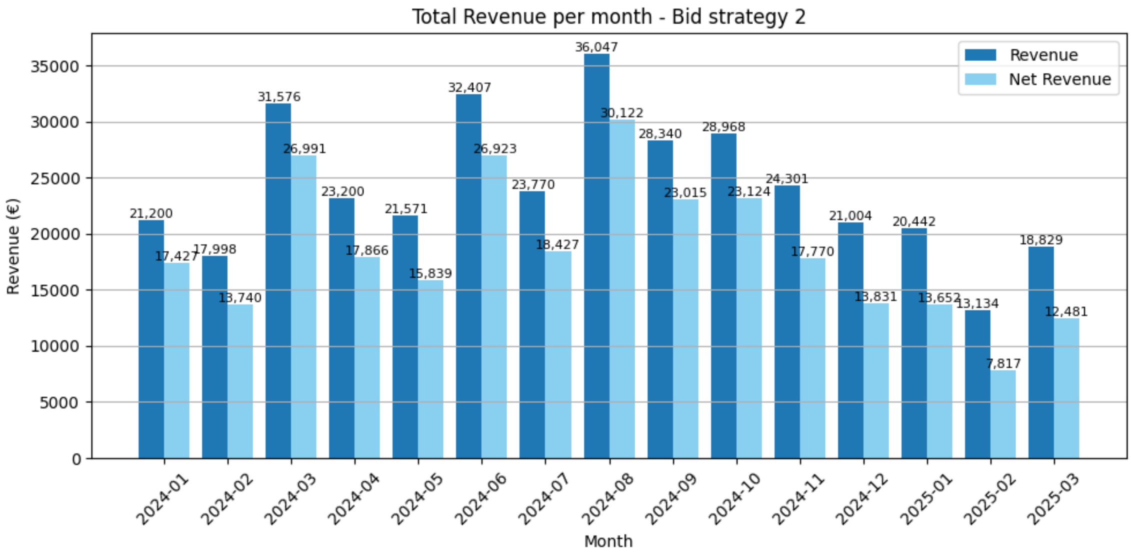


Figure 31: Total Revenue per month - Bid Strategy 2 with bids based on the DAM price and a constant upward margin of +€10 and downward margin of +€140 (Jan 2024 – March 2025)

Table 10: Simulation results per month - Bid Strategy 2 with bids based on the DAM price and a constant upward margin of +€10 and downward margin of +€140 (Jan 2024 – March 2025)

Month	Total revenue up (€)	Total revenue down (€)	Total revenue (€)	Total upward activations (volume)	Total downward activations (volume)	VWAP Up (€)	VWAP Down (€)	Degradation cost (€)	Net revenue (€)
01-2024	21672	-472	21200	69	82	313	6	3773	17427
02-2024	17631	367	17998	78	92	226	-4	4258	13740
03-2024	29250	2325	31576	85	99	345	-24	4585	26991
04-2024	22028	1172	23200	97	116	226	-10	5334	17866
05-2024	23169	-1598	21571	106	123	219	13	5731	15839
06-2024	29333	3073	32407	100	119	293	-26	5484	26923
07-2024	20918	2852	23770	98	115	213	-25	5343	18427
08-2024	35486	561	36047	109	128	326	-4	5925	30122
09-2024	27607	734	28340	99	114	280	-6	5325	23015
10-2024	30336	-1368	28968	107	127	284	11	5844	23124
11-2024	29084	-4783	24301	120	141	242	34	6531	17770
12-2024	23540	-2536	21004	132	155	178	16	7173	13831
01-2025	24897	-4455	20442	125	147	200	30	6790	13652
02-2025	20159	-7025	13134	97	115	207	61	5317	7817
03-2025	23143	-4315	18829	117	137	198	31	6347	12481

6.3 Bid Strategy 3: Intraday price-based

In Bid Strategy 3, the goal was to further improve results by using the last available intraday market (IDM) price, taken 25 minutes before the start of each ISP (at the time of bidding), as the reference price. Again, a fixed margin was then added to this reference for both upward and downward bids. By iterating through combinations of margin values, the optimal configuration was found to be a margin of 0 for upward bids (effectively bidding at the IDM price) and a margin of +200 for downward bids. See *Figure 32* and *Table 11*.

This strategy did not result in any new insights and did not lead to higher net revenue in any month compared to Strategy 2. One possible explanation is that it led to more activations without improved average prices. More fundamentally, this may be due to the fact that the last available trade is not a reliable predictor of the actual Dispatch price. Since this strategy relies on a single price point, it may fail to capture the broader market trend within the relevant 15-minute ISP. A more robust approach could involve averaging multiple recent IDM trades to form a more accurate price estimate. However, investigating this was beyond the scope of this research.

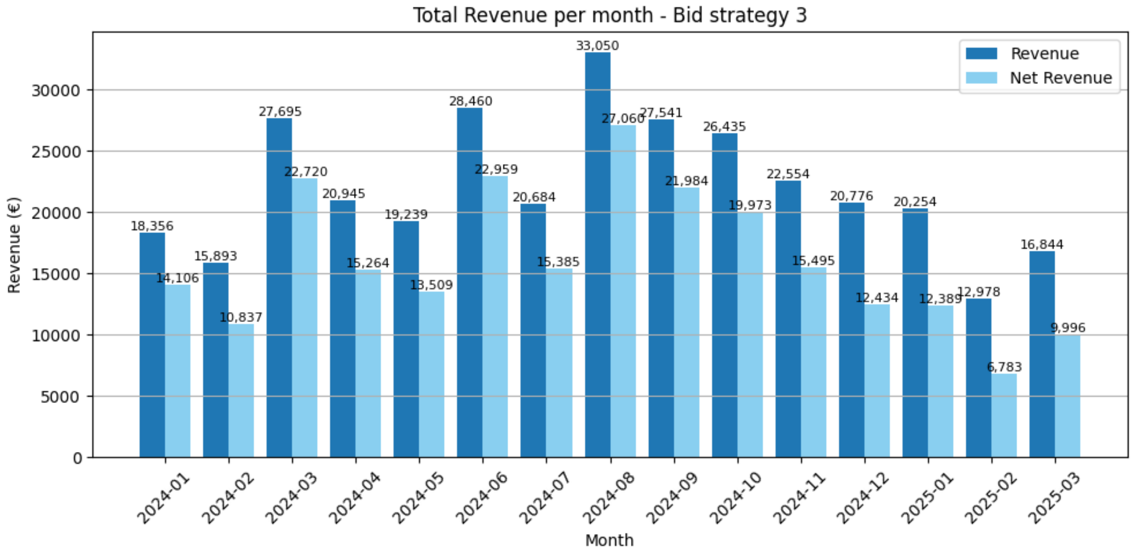


Figure 32: Total Revenue per month - Bid Strategy 3 with bids based on the IDM price and a constant upward margin of +€0 and downward margin of +€200 (Jan 2024 – March 2025)

Table 11: Simulation results per month - Bid Strategy 3 with bids based on the IDM price and a constant upward margin of +€0 and downward margin of +€200 (Jan 2024 – March 2025)

Month	Total revenue up (€)	Total revenue down (€)	Total revenue (€)	Total upward activations (volume)	Total downward activations (volume)	VWAP Up (€)	VWAP Down (€)	Degradation cost (€)	Net revenue (€)
01-2024	19763	-1407	18356	78	92	254	15	4249	14106
02-2024	16172	-279	15893	93	109	174	3	5056	10837
03-2024	26027	1668	27695	92	107	284	-16	4975	22720
04-2024	20651	295	20945	104	123	199	-2	5682	15264
05-2024	20978	-1739	19239	106	123	198	14	5729	13509
06-2024	26676	1783	28460	101	119	265	-15	5501	22959
07-2024	19176	1508	20684	98	114	197	-13	5299	15385
08-2024	33476	-426	33050	110	130	305	3	5990	27060
09-2024	27732	-191	27541	103	119	270	2	5557	21984
10-2024	29059	-2625	26435	118	140	246	19	6462	19973
11-2024	28549	-5995	22554	130	153	220	39	7058	15495
12-2024	24457	-3680	20776	154	180	159	20	8343	12434
01-2025	26819	-6565	20254	145	170	185	39	7865	12389
02-2025	21577	-8600	12978	113	134	190	64	6195	6783
03-2025	22180	-5336	16844	126	148	176	36	6848	9996

6.4 Bid strategy comparison

Table 12 presents the aggregated monthly results over the entire simulation period. The findings confirm the earlier observations. Strategy 1a results in relatively low activation volumes but achieves a very favorable upward VWAP. Strategy 1b increases the volume compared to 1a and sees a decline in VWAP, though the price spread remains sufficiently high to improve both total and net revenue. Strategy 2 further increases activation volumes, with a slightly lower upward VWAP, yet still maintains a spread that leads to the highest net revenue. Strategy 3 results in higher activated volumes, but lower total and net revenue. This is driven by the smaller spread between the VWAPs, which indicates that charging and discharging take place at less favorable prices. The increased activation also limits the ability to capture extreme high price peaks. As a result, some charge and discharge cycles have a price spread smaller than the degradation costs, which fails to improve net revenue.

Net revenue is the performance indicator used to select the best strategy, as the primary aim is to assess the relative revenue potential compared to passive balancing. As highlighted in green in Table 12 below, Strategy 2 achieves the highest net revenue and is therefore chosen for the comparison. The outperformance of strategy 2 is mainly due to its more effective balance between activated volume and price capture. By basing bids on the DAM, the strategy enables more dynamic activation (see Figure 51 in Appendix D) and avoids long periods with low activity such as with 1a and sometimes even with strategy 1b (see Figure 50 in Appendix D). For upward activation, bidding just above the DAM price improves the capture of minor price spikes without compromising the ability to capitalize on extreme price peaks. Strategy 3 leads to even more activation but generates less revenue due to less favorable price spreads.

Furthermore, *Figure 52 in* Appendix D presents a side-by-side bar chart of monthly net revenues, clearly illustrating that Strategy 2 consistently outperforms the other strategies throughout the simulation period, reinforcing its selection.

Table 12: Key performance indicator comparison of the considered bidding strategies – Results of the entire simulated period: 01/01/2024 -01/03/2025.

	Bidding strategy 1a	**Bidding strategy 1b**	**Bidding strategy 2**	**Bidding strategy 3**	Unit
Bidding prices	Constant up 140 down 90	Constant up 100 down 90	DAM margin up 10 margin down 140	ID margin up 0 margin down 200	
Total Revenue	€ 247,176	€ 316,341	€ 362,785	€ 331,707	€
Net revenue	**€ 221,639**	**€ 252,440**	**€ 279,025**	**€ 240,895**	**€**
Total activated upward volume	468	1,175	1,539	1,669	MWh
Total activated downward volume	552	1,382	1,811	1,963	MWh
Minutes activated upward	31,514	83,706	103,688	110,724	Minute
Minutes activated downward	60,311	112,895	146,974	160,556	Minute
VWAP upward	€ 555	€ 289	€ 246	€ 218	€/MWh
VWAP downward	€ -23	€ -17	€ -9	€ -23	€/MWh
Total degradation costs	€ 25,537	€ 63,901	€ 83,760	€ 90,809	€

6.5 Sensitivity analysis

A sensitivity analysis is performed on Bid Strategy 2 because it is identified as the best-performing strategy based on net revenue. By testing how sensitive its results are to key parameters, we can better understand the robustness of the bid strategy. While testing the bidding strategies and optimizing the most optimal bid prices and margins of the DAM and IDM prices, the sensitivity was already tested with respect to prices (see 3.3.7). This showed that extreme high upward bid prices or margins and extremely low downward bid prices/margins lead to almost no activation and low revenue, while low upward prices/margins and high downward bid prices/margins results in very frequent activation and high revenue. In this section the sensitivity is tested with regard to battery capacity and Round-trip efficiency.

6.5.1 Battery capacity

Table 13 shows the results of Bid Strategy 2 under varying battery capacities. As mentioned previously, the model simulates a pool of 1000 batteries, each initially with a capacity of 20 kWh and a maximum power output of 10 kW. The presented results are scaled by a factor of 10 to facilitate consistent comparisons, effectively representing a pool of 100 batteries. This part of the sensitivity analysis investigates how changing the battery capacity affects the results. Importantly, while battery capacity varies, the maximum power output remains constant, thus altering the capacity-to-power ratio. Maximum power is limited by household grid connections, whereas battery capacity can be expanded relatively easily in increments of 5 kWh modules. It is therefore valuable to examine how changing battery capacity influences net revenue. The table presents results for battery capacities of 10, 15, 20, 25, and 30 kWh, including the percentage differences of the performance indicators relative to each capacity level that is 5 kWh lower.

Table 13: Simulation results of Bid Strategy 2 under varying battery capacity

Battery capacity	**10KWh**	**15 KWh**	**Δ %**	**20 KWh (33,33%)**	**Δ %**	**25 KWh (25%)**	**Δ %**	**30 KWh (20%)**	**Δ %**
Total Revenue	€247,351	€318,900	29%	€362,785	13.8%	€388,851	7.2%	€408,433	5.0%
Net Revenue	€186,590	€243,677	31%	€279,025	14.5%	€299,422	7.3%	€314,976	5.2%
Total activated upward volume	1,116 MWh	1,382 MWh	24%	1,539 MWh	11.4%	1,643 MWh	6.8%	1,716 MWh	4.4%
Total activated downward volume	1,313 MWh	1,626 MWh	24%	1,811 MWh	11.4%	1,934 MWh	6.8%	2,021 MWh	4.5%
VWAP upward	€233,77 /MWh	€241.12 /MWh	3%	€245.75 /MWh	1.9%	€246.76 /MWh	0.4%	€248.16 /MWh	0.6%
VWAP downward	€-10.48 /MWh	€-8.88 /MWh	-15%	€-8.54 /MWh	-3.8%	€-8.58 /MWh	0.5%	€-8.72	-1.6%
Total degradation costs	€60,760	€75,223	24%	€83,760	11.3%	€89,429	6.8%	€93,456	4.5%

The results demonstrate that increasing battery capacity leads to higher total and net revenues, but the incremental gains diminish as the overall capacity grows. One reason for this diminishing increase is that an absolute capacity increment of 5 kWh represents a relatively smaller increase at higher total capacities. Nevertheless, even the absolute revenue gains clearly exhibit a diminishing trend. This suggests that at some point, further increasing battery capacity may no longer justify the additional investment costs. To identify the optimal battery capacity, a cost-benefit analysis is needed, assessing at which point the additional cost of increasing capacity outweighs the incremental revenue generated.

Furthermore, the results highlight the model's significant sensitivity to battery capacity, which is logical since capacity constraints directly limit the volume of activations due to SoC restrictions. Remarkably, even at relatively low capacities (10 kWh), substantial revenue is still generated. This can be explained by the frequent alternation between upward and downward activations, maintaining SoC within a range that still allows the battery to capture the majority of the price peaks effectively. Batteries with higher capacity mainly have an advantage during prolonged periods of predominantly upward or downward activation, enabling higher activation volumes and thus generating greater revenues.

6.5.2 Round-trip efficiency

Table 14 presents the results of Bid Strategy 2 under varying round-trip efficiency levels: 85%, 90%, 95%, and 100%. The previously discussed results used an efficiency level of 85%, closely reflecting the actual efficiency of Zonneplan's home batteries. The table includes the percentage differences relative to the efficiency level 5 percentage points lower (from 85% to 90%, 90% to 95%, and 95% to 100%).

Total revenue shows incremental improvements ranging from 1.9% to 1.5%, demonstrating a slightly diminishing trend toward 100% efficiency. The improvement in revenue is not proportional to the 5% increments in efficiency, confirming a non-linear relationship between efficiency and revenue.

As anticipated, total upward and downward activated volumes reach parity at 100% efficiency. This parity occurs because, at 100% efficiency, all energy charged (downward activation) is available for discharge. With efficiency losses, upward activation volume remains lower, as only a portion of the downward activation is effectively stored, and additional losses occur during discharge.

The upward VWAP shows minimal sensitivity, reflecting the limited change in upward activation volume and suggesting the timing of upward activation remains consistent across different efficiency levels. The downward VWAP shows a slightly larger variation due to the bigger change in downward activation volume.

Additionally, a small reduction in degradation costs is observed, attributed to the decreased absolute volumes fueled by the decrease in downward activation volume. This also explains why net revenue increases slightly more than total revenue.

In conclusion, at higher efficiency levels, improvements yield only slight increases in net revenue, indicating low sensitivity. Thus, investments aimed solely at increasing battery efficiency or employing higher-efficiency batteries are unlikely to yield significant profitability gains, but this should be explored further with a cost-benefit analysis. The observed parity in upward and downward activated volumes at 100% efficiency validates the model's operational consistency.

Table 14: Simulation results of Bid Strategy 2 under varying levels of round-trip efficiency

Round-trip efficiency	**85%**	**90%**	**Δ %**	**95%**	**Δ %**	**100%**	**Δ %**
Total Revenue	€362,785	€369,569	1.9%	€375,924	1.7%	€381,657	1.5%
Net Revenue	€279,025	€286,854	2.8%	€294,219	2.6%	€300,866	2.3%
Total activated upward volume	1,539 MWh	1,566 MWh	1.8%	1,591 MWh	1.6%	1,616 MWh	1.6%
Total activated downward volume	1,811 MWh	1,741 MWh	-3.9%	1,676 MWh	-3.7%	1,616 MWh	-3.6%
VWAP upward	€245.75 /MWh	€245.84 /MWh	0.0%	€245.81 /MWh	0.0%	€245.79 /MWh	0.0%
VWAP Downward	€-8.54/ MWh	€-9.00 /MWh	5.4%	€-9.19 /MWh	2.1%	€-9.55 /MWh	3.9%
Total degradation costs	€83,760	€82,714	-1.2%	€81,705	-1.2%	€80,790	-1.1%

6.6 Passive balancing vs. Bid Strategy 2

This section presents the comparison between the passive balancing results, which include both Ex-Post trading and internal and external portfolio advantages and the results of aFRR Bid Strategy 2. To enable a meaningful comparison, also for the passive strategy net revenue is calculated, based on its settled charged and discharged volumes. *Figure 49* in Appendix D presents the net revenue version of the earlier figure introduced in Chapter 4.

In this comparison, the results from Bid Strategy 2 are based on a simulation without charge and discharge inefficiencies as presented in the sensitivity analysis. This choice was made to align with the passive backcast, where efficiency losses were also not considered. As a result, the Bid Strategy 2 outcomes shown here are slightly improved compared to earlier results. Notably, upward and downward activation volumes are now equal, whereas in the simulations with efficiency losses, more Downward activation (charging) occurred than upward activation (discharging). For the purpose of this comparison, the focus is on a fair and consistent relative evaluation. Therefore, the assumption to exclude efficiency losses was considered most appropriate.

6.6.1 Net Revenue

Figure 33 presents the net revenue comparison between passive balancing and aFRR Bid Strategy 2. What stands out immediately is that the net revenue from aFRR is higher than that of passive balancing over the entire period. However, the difference varies from month to month. In some months, such as July 2024, the net revenue from aFRR is nearly twice as high, while in others, such as March 2025, the difference is considerably smaller.

Another notable observation is that the month-to-month revenue pattern is nearly identical for both strategies. This is expected, as both are based on the same underlying market conditions and largely the same prices. This supports the conclusion that, at least in broad terms, the aFRR bidding simulations produce realistic and consistent results.

The expectation that the difference between the two strategies would grow due to the increasing prevalence of Regulation State 2 is not clearly visible in the results. This may be due to the effect being overshadowed by other factors. One important factor is that the revenue results for passive balancing in the first three months of 2025 are based on an improved price forecasting model, which brings those results closer to the aFRR strategy outcomes.

The difference in net revenue between the two strategies is further analyzed in the following sections, based on activation volumes, VWAP, and the breakdown of upward and downward revenue.

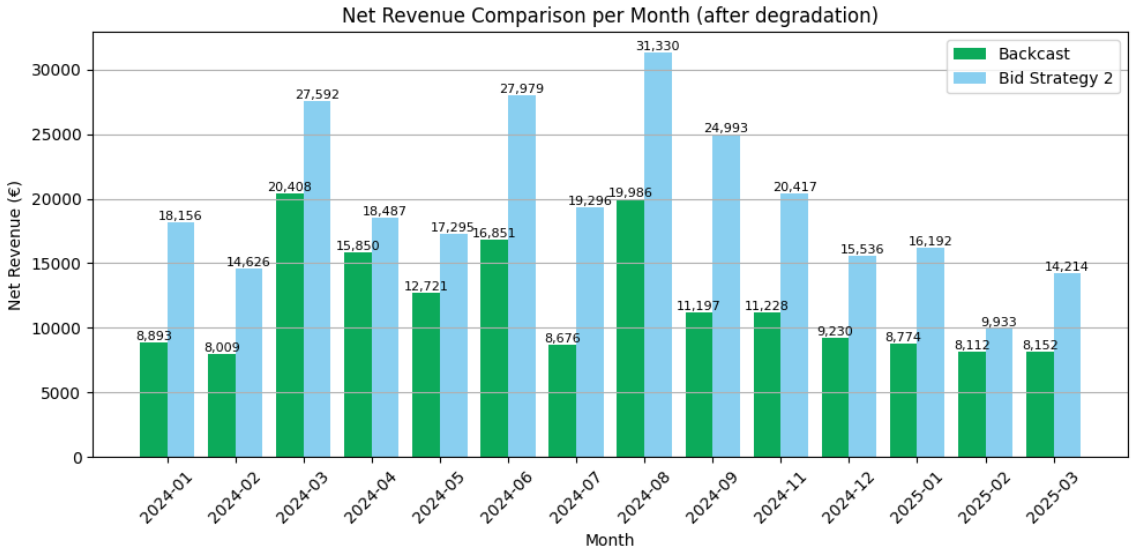


Figure 33: Net Revenue comparison per month – Passive balancing vs Bid Strategy 2 (Jan 2024-March 2025)

6.6.2 Upward (discharge) and downward (charge) volumes

Figure 34 shows the activated upward volume from aFRR Bid Strategy 2 compared to the settled discharge volume from the passive balancing strategy. It is important to note that, in passive balancing, discharging can occur at any time, whereas in aFRR, upward activation only occurs when TenneT explicitly activates upward regulation. Since charge and discharge efficiency is not applied in either case for this comparison, the upward and downward volumes (i.e., discharge and charge volumes) are identical. Therefore, only the upward volumes are presented.

Once again, the Figure shows that both strategies follow a similar monthly pattern. In months with more upward activation, the passive balancing strategy also tends to show higher discharge volumes. However, aFRR consistently results in higher volumes across the entire period, with the gap between the two strategies increasing noticeably toward the end of the simulation period.

This growing difference could be attributed to the ability of aFRR bidding to take advantage of the trend of increasing activation volumes and higher prices over longer durations, as discussed in Chapter 5. In contrast, the lower volumes in the passive strategy may be due to the rising frequency of RS 2, which reduces the availability of favorable charging and discharging moments for passive balancing.

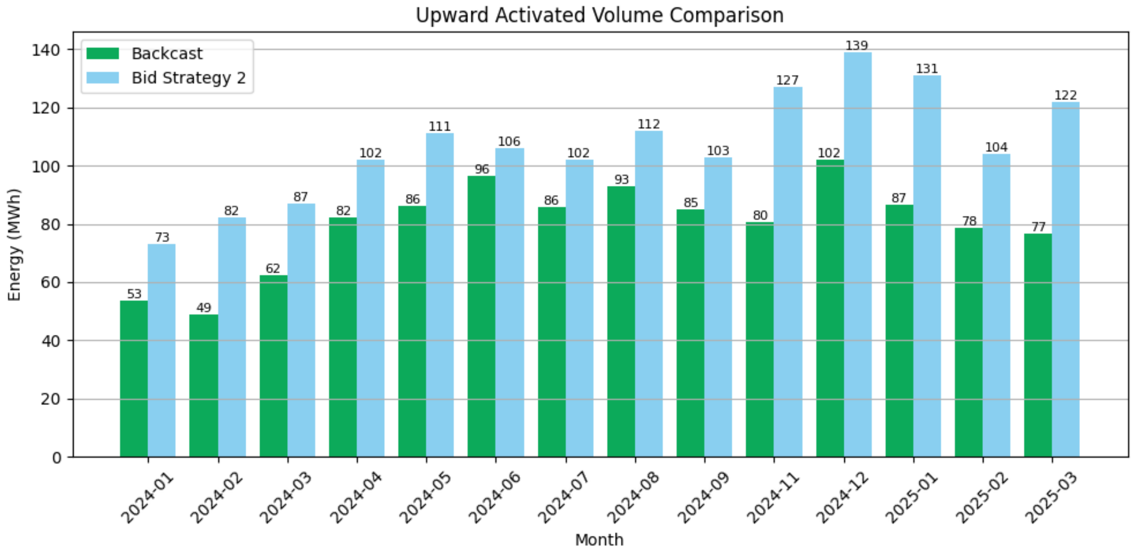


Figure 34: Discharged/Upward Activated Volume comparison per month - Passive balancing vs Bid Strategy 2 (Jan 2024-March 2025)

6.6.3 Volume-Weighted average upward (discharge) and downward (charge) prices

The upward and downward (i.e. discharge and charge prices) volume-weighted average prices (VWAP) are shown in *Figure 35* and *Figure 36*, respectively. For the upward VWAP, a consistent month-to-month pattern is observed across both strategies. Until September 2024, the aFRR bid results display more favorable (higher) upward prices than passive balancing. After this point, passive balancing begins to show more favorable prices. This shift implies that the difference in net revenue between the strategies in the latter part of the period cannot be attributed to superior upward (discharging) prices from the aFRR strategy.

The downward VWAP (charging prices) shows a more varied pattern, with larger differences between the two strategies across months. Interestingly, in contrast to the upward VWAP, passive balancing achieves more favorable charging prices in the earlier months, while aFRR bidding becomes more favorable toward the end of the simulation period. This partially explains the improved net revenue performance of aFRR bidding during those later months, as it was able to charge at lower prices.

A relevant benchmark is the average Dispatch Down price, as presented earlier in *Figure 21* and *Figure 22* in Chapter 5. In earlier months, passive balancing was able to charge at better prices than the average Dispatch Down price. However, this advantage disappears near the end of the simulation period. Meanwhile, the downward VWAP from aFRR bidding remains close to the average monthly Dispatch Down prices throughout the period. This suggests that the earlier identified limitation related to downward activation prices does not result in distorted or inflated charging prices in the aFRR bid strategy.

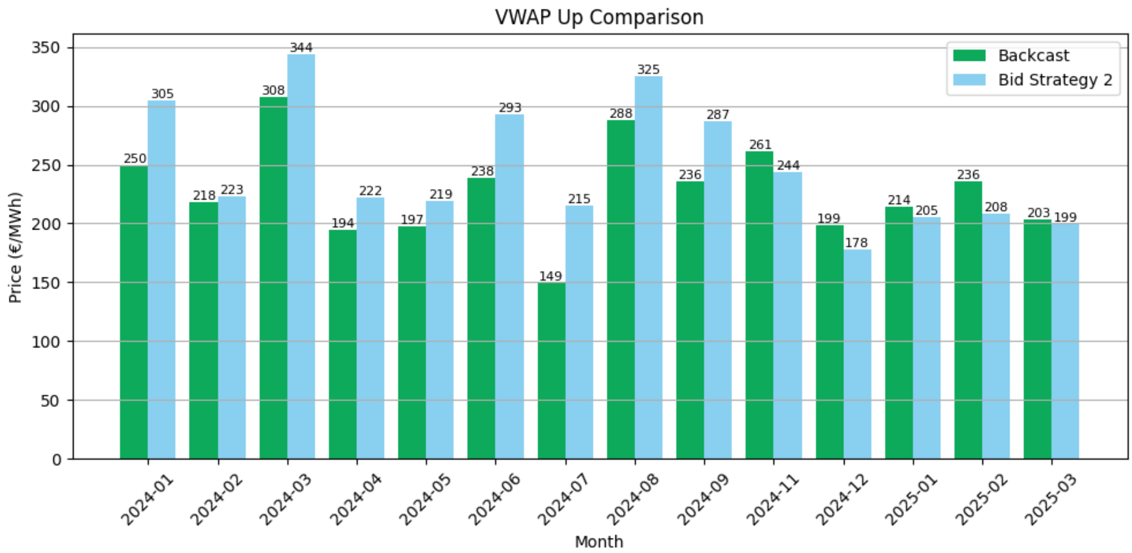


Figure 35: Discharged/Upward activated Volume-Weighted Average Price comparison per month - Passive balancing vs Bid Strategy 2 (Jan 2024-March 2025)

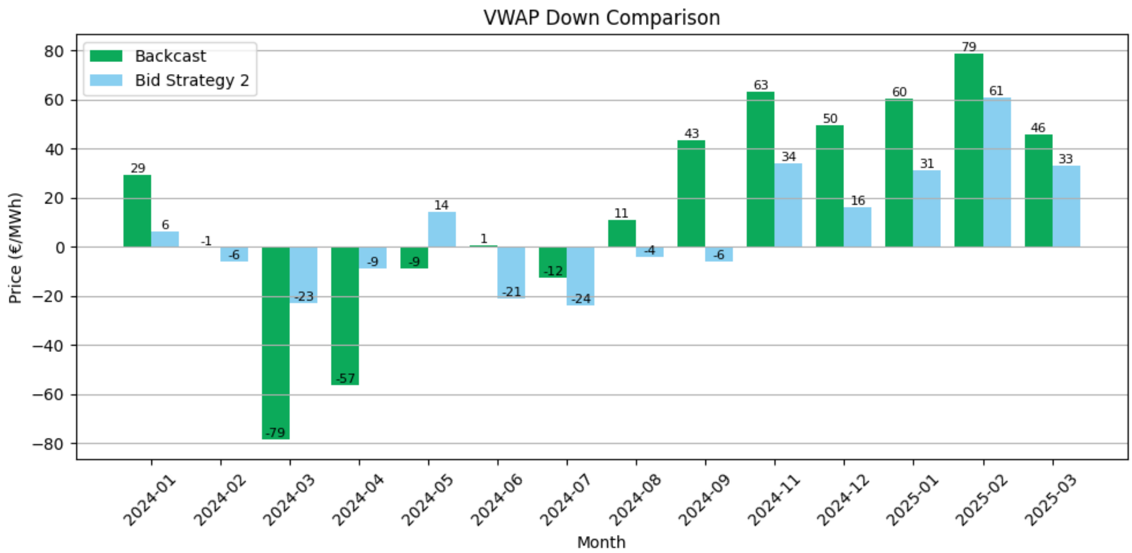


Figure 36: Charged/Downward activated Volume-Weighted Average Price comparison per month - Passive balancing vs Bid Strategy 2 (Jan 2024-March 2025)

6.6.4 Upward (discharge) and downward (charge) revenue

Figure 37 and *Figure 38* present the monthly upward and downward revenues from aFRR Bid Strategy 2, compared to the corresponding discharging and charging revenues from the passive balancing strategy. It is important to note that these values reflect gross revenue, meaning degradation costs have not yet been subtracted. As a result, the differences between strategies appear smaller than in the net revenue comparison.

As explained earlier, passive balancing also incurs degradation costs on unsettled volumes. This leads to a relatively lower net revenue performance compared to the aFRR bid strategy, where degradation costs are only applied to activated volumes.

For both strategies, the overall downward trend in total revenue toward the end of the period can primarily be attributed to rising costs of downward regulation or charging. In contrast, revenues from upward regulation (discharging) remain more stable, suggesting that increasing downward prices play a more significant role in the observed revenue decline.

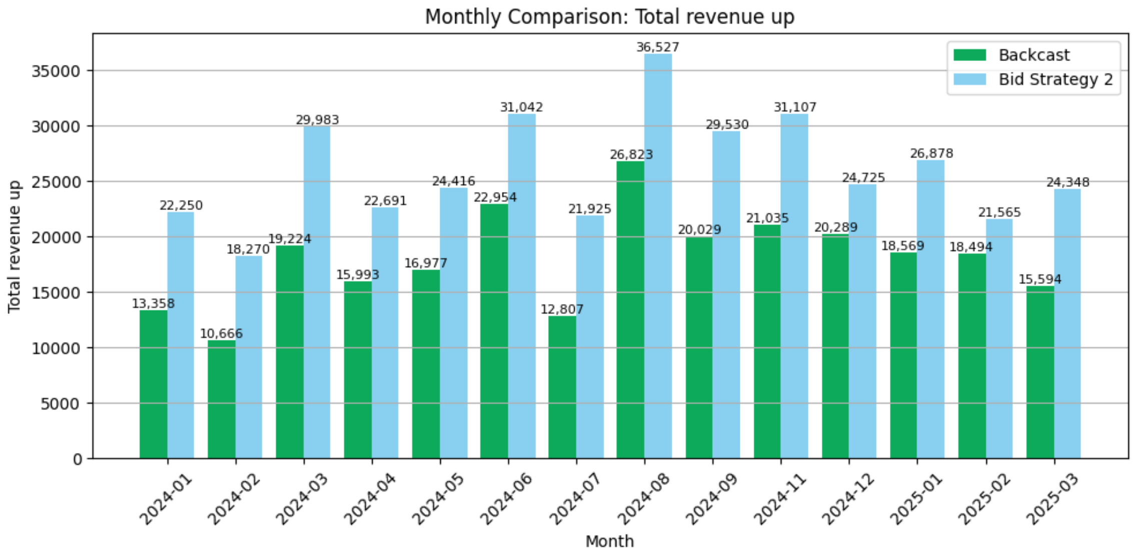


Figure 37: Total Discharged/ Upward activated revenue comparison per month - Passive balancing vs Bid Strategy 2 (Jan 2024-March 2025)

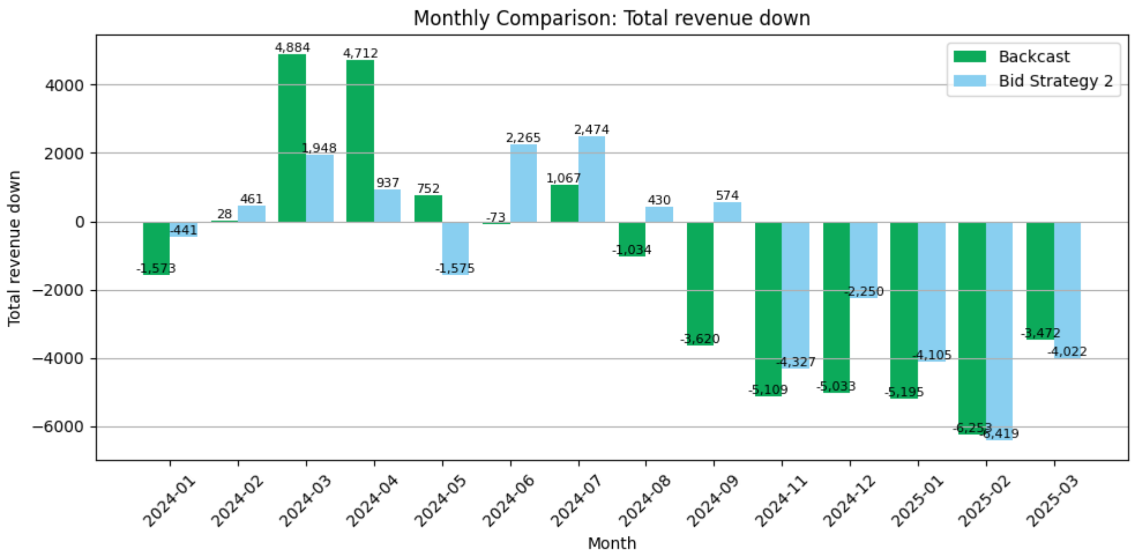


Figure 38: Total Charged/ Downward activated revenue comparison per month - Passive balancing vs Bid Strategy 2 (Jan 2024-March 2025)

6.6.5 Bid Strategy 2 – Revenue and Volumes by regulation state

Finally, *Figure 39* and Figure 40 present the revenue and activation volumes of Bid Strategy 2, segmented by regulation state. These can be directly compared to the Figures previously shown in Chapter 4 for the passive balancing strategy. Although regulation states are not directly relevant to aFRR, this analysis helps illustrate why aFRR is more effective in supporting system balance. It also shows that aFRR continues to offer significant revenue potential during RS2 intervals, where passive balancing strategies are unable to generate value because of the reversed pricing risk.

Earlier Figures of passive balancing volumes by regulation state showed that charging and discharging actions often occurred in the opposite direction of what the system required. This inefficiency does not occur with aFRR participation. Additionally, unlike passive balancing, all activated volume in aFRR is settled, rather than only the net position at the end of the ISP. This underscores the higher financial and operational efficiency of participating in the aFRR market.

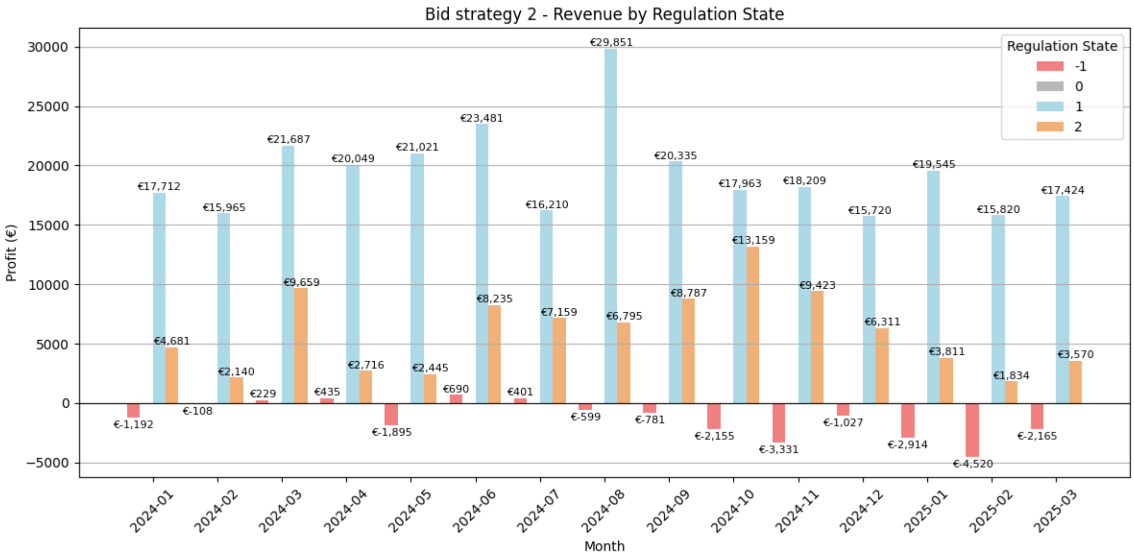


Figure 39: Monthly Revenue by regulation state – Bid Strategy 2 (Jan 2024-March 2025)

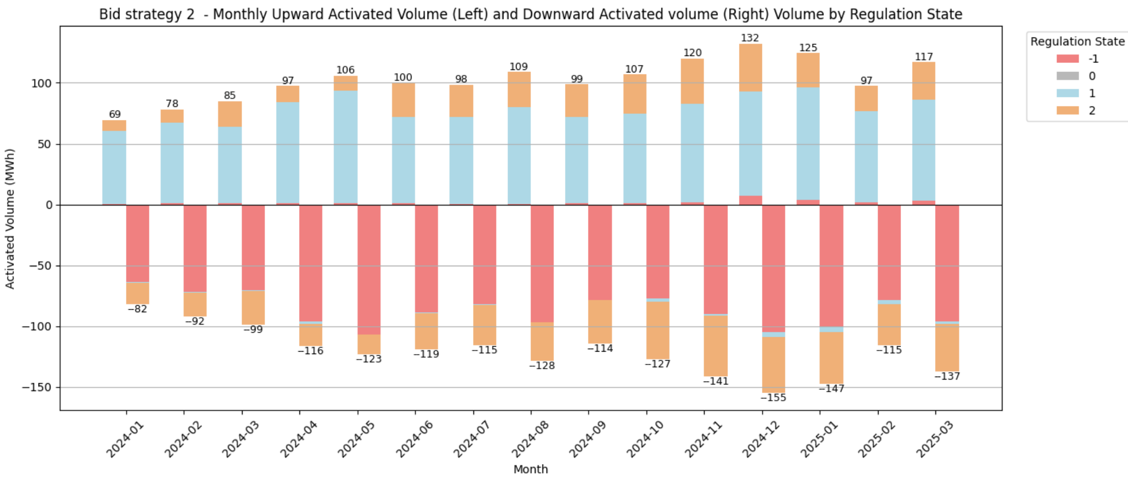


Figure 40: Monthly Upward Activated Volume (left) and Downward Activated Volume (right) by regulation state – Bid Strategy 2 (Jan 2024-March 2025)

6.7 Conclusion

SQ3: What are possible bidding strategies for Zonneplan to participate in the rapidly evolving Dutch aFRR market and how do they perform?

All three considered bidding strategies appear viable for Zonneplan's participation in the evolving Dutch aFRR market. Strategy 1 was tested in two variations using constant bid prices. Strategy 1a applied fixed upward and downward bid prices with a fixed spread and was able to achieve relatively high net revenue with only limited activation, thanks to the efficient capture of high price peaks. Strategy 1b also used constant prices but without a fixed spread, resulting in higher activation and revenue, though with less favorable spreads. Strategy 2, linking bid prices to Day-Ahead market prices with a fixed margin, performed best overall, achieving strong activation levels without long periods of inactivation while maintaining favorable spreads, resulting in the highest net revenue. Strategy 3, based on Intraday prices, yielded more activated volume but underperformed in terms of net revenue due to narrower price spreads.

7 Discussion

This chapter discusses the core comparison between passive balancing and aFRR Bid Strategy 2 as presented in chapter 6, followed by the key limitations of the research. It then outlines the practical and broader implications of the findings and concludes with the study's contribution to the academic literature.

7.1 Discussion of passive balancing versus aFRR results

The core of this research is the direct comparison between the best-performing aFRR strategy (Bid Strategy 2) and Zonneplan's passive balancing backcast in terms of net revenue. The results demonstrate a decisive advantage for active aFRR participation.

Net Revenue

Active participation in the aFRR market with DAM price based bidding consistently generated higher net revenue than passive balancing throughout the analyzed period. While both strategies exhibited similar monthly revenue patterns, reflecting their dependence on underlying market conditions, aFRR's outperformance was notable, sometimes nearly doubling passive balancing's net revenue.

Activated Volumes

aFRR consistently resulted in higher activated volumes (both upward and downward) compared to the settled volumes from passive balancing. This gap widened towards the end of the simulation period, suggesting that aFRR is better positioned to leverage increasing activation opportunities in the evolving market. The lower volumes in passive balancing may be partly due to the rising frequency of Regulation State 2 (RS2) periods, which limit favorable charging and discharging moments for passive balancing.

Volume-Weighted Average Prices (VWAP)

The upward VWAP showed that aFRR achieved more favorable prices than passive balancing until September 2024, after which passive balancing occasionally had better upward prices. For downward VWAP (charging prices), passive balancing was more favorable in earlier months, while aFRR became more advantageous later in the period, allowing for charging at lower costs.

System-Level Impacts

Beyond higher revenue, active aFRR participation offers a superior contribution to grid stability. Unlike passive balancing, where uncoordinated responses can lead to "overshooting" and exacerbate imbalances, aFRR activations are directly controlled by TenneT. This ensures that battery responses are precisely aligned with system needs, mitigating oscillations and potentially reducing the frequency of RS2 periods. Furthermore, aFRR participation allows for full remuneration of all activated volumes, unlike passive balancing where on average approximately 13% of energy delivered is lost due to simultaneous charging and discharging within the same ISP and is not recognized in settlement. Crucially, aFRR participants can profit from high-price events during RS2, where passive balancing is financially disadvantaged due to dual pricing.

7.2 Limitations

This research provides valuable insights into the comparative performance of passive balancing and aFRR market participation for aggregated home batteries. However, it is important to acknowledge several limitations that could influence the generalizability and precision of the findings.

7.2.1 Passive balancing backcast

- **Data availability:** The passive balancing backcast data was limited to 15 months (January 2024 - March 2025, with October 2024 excluded). While this period captures recent dynamics, a longer historical dataset would enhance statistical significance and allow for more robust trend analysis.
- **Multiple price forecasting models:** The final three months of the passive balancing backcast (January–March 2025) were based on a different price forecasting model than the one used for the earlier months. These months were included to enable year-over-year comparison. However, the use of different models complicates drawing consistent conclusions across the entire period. The newer forecasting model appeared to perform better, resulting in more effective activation and less unsettled volume. This likely mitigated some of the negative impact of the increased frequency of RS2 ISPs on performance during that time.
- **100% efficiency:** The passive balancing backcast assumed 100% charging/discharging efficiency and no technical failures or disruptions. In reality, efficiency losses and operational constraints due to household consumption would reduce actual performance. This means the passive balancing results presented might represent an optimistic upper bound. To cope with this limitation with the direct comparison with the aFRR bid simulations, the efficiency was set to 100% for the results used of Bid Strategy 2 in the comparison.
- **Balance delta delay**: Throughout the backcasted period, the balance delta delay was set at 5 minutes, which reduced the passive balancing performance in months where the actual delay was only 2 minutes. This simplification was made to enable a consistent and meaningful comparison across months, and because at the time, a 5-minute delay was in effect. However, as of July 2025, TenneT reduced the balance delta delay back to 2 minutes [11]. This change could improve the effectiveness of passive balancing, potentially narrowing the performance gap with aFRR participation.

7.2.2 aFRR market analysis

- **Rapidly evolving and complex aFRR market:** The dynamics of the aFRR market, including the bidding ladder, activation prices, and activated volumes, are subject to a wide array of influences and often lack transparency. This complex interplay of factors means that understanding market behavior, establishing reliable patterns, or conducting robust analyses over time is inherently complicated.
- **Weather influence:** Trends in the aFRR market are strongly influenced by weather conditions. High variability in solar and wind generation makes it challenging to draw firm conclusions from year-to-year comparisons. Differences in activation prices and activated volumes between years can often be attributed to weather fluctuations, particularly during months with unstable wind and solar output. As a result, isolating the impact of other factors, such as the introduction of PICASSO, becomes difficult. Observed changes may reflect weather-driven effects rather than structural shifts in market design or participant behavior.
- **Bidding behavior:** The aFRR market is currently composed of a relatively small number of participants, meaning that changes in the bidding strategies of just a few influential actors can significantly affect market outcomes. This may have contributed to some of the observed trends and introduces uncertainty when interpreting the results. Furthermore, as more BESS aggregators enter the market, incumbent players may adapt their strategies in response to

increased competition. Such shifts could alter market dynamics and limit the long-term applicability of the bidding strategies evaluated in this study.

7.2.3 aFRR bidding simulations

- **Minute-Level Activation:** The aFRR simulation used minute-level price snapshots to approximate activation, rather than the actual 4-second delta setpoints from TenneT's LFC. This simplification may not fully capture the nuances of real-time activations.
- **Instantaneous Power Changes:** The model assumes instantaneous changes in power output, neglecting ramp-up and ramp-down constraints. This simplification is an idealization. In reality, battery systems respond rapidly, though not instantly, primarily due to control signal delays and minimal physical ramp-rate constraints.
- **Perfect Adherence:** It was assumed that activated volume is exactly equal to delivered and settled volume, implying perfect adherence to dispatch signals. In practice, deviations can occur, leading to penalties or reduced payments, reducing the performance of aFRR participation.
- **Price-Taker Assumption:** The model assumed that the simulated battery acts as a price-taker, meaning its bidding decisions do not influence the marginal clearing price. This assumption may not hold if aggregated BESS capacity and large-scale BESS grows significantly, potentially leading to a strong influence on prices.
- **Historic data:** The simulation results are based on historic data. Although recent data was used, this gives no guarantees for future results as market dynamics can change quickly.
- **Optimization method:** The constant bid prices in strategy 1a and 1b, as well as the fixed margins in strategies 2 and 3, were selected by looping through different parameter combinations using historical data. While this method identifies settings that performed well over the full simulation period, there is no guarantee that these values will remain optimal under future market conditions. However, since no advanced optimization methods were used, the risk of overestimating aFRR performance remains limited, even though the results were optimized using past data.
- **Bidding strategies:** Only three bidding strategies were considered in this study, limiting the analysis to a narrow set of possible bidding approaches. By restricting the scope in this way, the research may have overlooked other potentially effective strategies.
- **Limited market scope:** This study was limited to a direct comparison between passive balancing and aFRR bidding strategies. Strategies concerning other markets such as FCR, mFRR, IDM or DAM or multi-market strategies were not considered.

7.2.4 General limitations

- **Comparing passive balancing with aFRR:** While both passive balancing and aFRR bidding strategies are influenced by the same underlying trends in the aFRR market, their performance shows significant overlap over time. This makes it difficult to isolate and attribute differences in performance to the control strategy itself rather than to external market conditions.
- **Lack of prior research:** As highlighted in the literature review, there is a clear lack of prior research on passive balancing and aFRR bidding strategies applied to the Dutch market using recent market data. This limited the availability of established methods or benchmarks to build upon, giving the study a primarily exploratory character. As a result, both the approach and findings are less robust than those grounded in more mature research fields. Nonetheless, the results are highly valuable precisely because they address this gap, offering new insights in an underexplored area.
- **Limited expert validation:** Interviews with market experts and representatives from TenneT were initially planned to validate the findings of this research. However, despite multiple attempts, it proved difficult to secure participation. As a result, the study lacks external expert

validation, which limits the robustness of its conclusions. This challenge highlights a broader issue involving TenneT, aFRR market participants, and operators employing passive balancing: the market lacks transparency. Many commercial actors are reluctant to share strategic insights, and there is a limited number of experts who fully understand the complexity of the aFRR market and are willing to engage openly. This lack of transparency hinders knowledge exchange and may reduce the efficiency and adaptability of the market. If TenneT aims to facilitate a transition from passive balancing to active aFRR participation, particularly for operators of fast-ramping assets, it should lead by example in promoting openness and improving access to information.

7.3 Practical implications

The findings have significant practical implications for the main stakeholders as discussed below.

For Home Battery Aggregators (like Zonneplan):
There is a clear and compelling financial case to transition from a business model centered on passive balancing to one focused on active participation in the aFRR market. Such a shift would not only unlock higher and more stable revenue streams, but also better align aggregator operations with TenneT's objectives for maintaining grid stability, thereby supporting a more sustainable long-term business model.

Given the current limited BESS competition, aggregators are advised to move quickly toward active aFRR bidding. Aggregators should prioritize upgrading their systems to meet TenneT's operational requirements and effectively respond to setpoint instructions. Initially, DAM price-based bidding (strategy 2) can serve as entry strategy. However, this approach should be improved further by integrating advanced price forecasting with MILP optimization, similar to methods currently used for passive balancing.

However, until the transition to aFRR is made and given the rapidly evolving nature of the market, it is essential to continuously monitor and adapt to several key developments:

- **Regulation state distribution:** Up to now, the increase in Regulation State 2 (RS2) has primarily come at the expense of Regulation State 0, with minimal impact on the frequency of states -1 and 1. However, if RS2 starts to rise at the cost of Regulation States -1 and 1, the financial attractiveness of passive balancing is expected to decline considerably, since these states currently offer the most favorable conditions for passive balancing revenues.
- **Frequency of high price peaks:** Large price spikes significantly impact revenue potential for both passive balancing and aFRR. Should more high-price events begin to occur during RS2 periods, this will further tilt the advantage toward active aFRR participation.
- **Results of ex-post trading and portfolio advantages:** At present, ex-post trading combined with internal and external portfolio effects helps mitigate financial exposure during RS2. However, this situation may evolve. If continuing to deploy a passive balancing strategy, it will be important to explore ways to further optimize ex-post trading and especially to improve the management of internal portfolio advantages, as these represent the greatest potential to enhance profitability and reduce RS2-related risks.
- **Transition to quarter-hour DAM blocks:** Current asset optimization models for passive balancing are built on historical hourly data, which often show elevated prices and a higher frequency of RS2 in the first quarter-hour. If these dynamics change with the move to 15-minute blocks as scheduled for September 2025 [50], these models will need to be recalibrated to maintain effectiveness.
- **Potential ramp rate restrictions:** New ramp-up and ramp-down constraints on passive balancing, as may be imposed by the ACM [51], could limit operational flexibility and make active participation in the aFRR market even more attractive by comparison.

- **Introduction of 4-hour aFRR capacity blocks:** With TenneT planning to introduce 4-hour capacity products in Q4 2025 [12], it will be important to prepare to integrate these into bidding and operational strategies, potentially unlocking an additional revenue stream.
- **Potential new aFRR product for fast-responding assets:** TenneT is currently considering the introduction of a specific aFRR product targeted at assets with high response speeds [12]. What this would mean for market dynamics and whether it would make aFRR participation even more attractive should be closely monitored.
- **TenneT's system measures to reduce oscillations:** Ongoing efforts by TenneT to minimize frequency oscillations should be carefully observed, as these could alter the relative benefits of passive balancing compared to providing active reserves.
- **Increase in Flexible Resources:** The growing availability of large-scale and aggregated BESS is expected to significantly impact the aFRR market. As more batteries enter, competition will intensify, potentially driving down aFRR prices. This could force batteries to bid closer to their opportunity costs, which would be influenced by potential revenues from the DAM and IDM.

By actively tracking these developments and maintaining flexibility in strategic decisions, BESS aggregators can position themselves to capitalize on market developments.

For the TSO (TenneT):
This research reinforces TenneT's concerns that passive balancing is a major contributor to the pronounced oscillations observed in the net system frequency. Batteries often charge or discharge in ways that oppose system needs and are causing overshoots because they respond so quickly to prices. It is encouraging for TenneT that aFRR also provides a clear financial incentive for BESS aggregators and large-scale BESS operators, increasing the likelihood they will participate in the aFRR market. This allows TenneT to use the fast ramp-up and ramp-down capabilities of batteries to respond more precisely and effectively to imbalances. As more parties transition to aFRR, passive balancing will naturally decrease, reducing its current impact on the grid.

For TenneT, it is important to prepare for the integration of aggregated BESS into their operations and ensure the transition goes smoothly. They should also maintain policies that keep aFRR participation more attractive than passive balancing, to prevent operators from reverting to passive strategies.

For Home battery owners:
This research shows that while income from passive balancing has been declining, participating in aFRR through an aggregator could help maintain profitability and ensure a reasonable payback period. In the long term, intraday and day-ahead arbitrage are expected to become more profitable, making investments in home batteries worthwhile both now and in the future. Homeowners do not need to take action themselves, as aggregators can manage and optimize their batteries on their behalf.

7.4 Broader implications

The findings also have broader relevance, of which a selection of key implications is presented below.

Large-scale battery operators
This research focused on passive balancing strategies as applied by home battery aggregators and explored potential aFRR bidding strategies for these actors. However, despite some operational differences, the findings are also relevant to operators of large-scale batteries and aggregators managing such systems. In fact, the operational challenges associated with controlling one or a few large batteries are often less complex, and these systems tend to integrate more easily with TenneT's infrastructure. This is mainly because fewer individual connections are involved, and fewer data

needs to be exchanged. Based on the results of this study, it is expected that also large-scale batteries will increasingly participate in the Dutch aFRR market, particularly in light of the rapid growth in new installations.

Relevance in European context

This study focused on the Dutch imbalance settlement system and aFRR market. While there is some alignment between imbalance frameworks across Europe, significant national differences remain. For example, imbalance settlement rules are not yet fully harmonized, unlike aFRR market regulations, which have been gradually converging in the lead-up to their integration through the European PICASSO platform. In Germany, passive balancing is not permitted, and BRPs are required to actively minimize portfolio imbalance. In contrast, Belgium does allow passive balancing but applies a different settlement mechanism, using a single-price system. The Netherlands also uses single pricing under normal conditions but switches to dual pricing during Regulation State 2, which introduces significant risks for passive balancing. Furthermore, imbalance prices vary greatly between countries, making it difficult to compare the potential of passive balancing, even in markets with similar structures.

Although aFRR market design is becoming more standardized across Europe, significant differences remain in activation prices, volumes, and frequency, largely due to variations in climate and electricity mix. Nevertheless, the principle behind Bid Strategy 2, basing bids on the Day-Ahead Market (DAM) price, may also be applicable in other countries, since a similar relationship between DAM and aFRR prices exist across European markets. Still, actual performance will depend heavily on local market dynamics.

Shift in market dynamics by increased competition

If home battery aggregators and large-scale battery operators begin participating in the aFRR market at scale, significant shifts in market dynamics are expected. The bidding ladder is currently dominated by gas-fired power plants. Increased competition and a growing supply of flexible capacity could drive down average aFRR prices and reduce the frequency of price spikes. However, as gas plants are phased out or pushed out of the market by this competition, scarcity pricing and price volatility could rise again. The long-term value of aFRR participation as a business model for home battery aggregators will therefore depend on how these developments unfold. In the short term, both revenue certainty and opportunity appear strong. It is therefore recommended that aggregators make the transition to aFRR participation soon and closely monitor ongoing market developments.

Impact on the PICASSO Platform

Greater participation by home battery aggregators and large-scale BESS operators in the Dutch aFRR market will influence PICASSO member states and market dynamics. Dutch aFRR capacity is already relatively cost-effective and is frequently activated by PICASSO to address imbalances in other countries. While PICASSO activations do not directly affect Dutch imbalance prices, they do result in higher activation volumes, which can indirectly raise average Dutch aFRR prices. As more Dutch aFRR capacity becomes available and competition reduces prices, PICASSO activations of Dutch resources are likely to increase, but limited by cross-border exchange capacity. While the exact impacts are uncertain, a larger supply of Dutch fast-responding aFRR capacity should in principle support better system balancing across member states and help reduce imbalance prices. To preserve sufficient domestic fast responding battery capacity to manage local oscillations, it may be prudent for the Netherlands to reserve a portion of this capacity outside of PICASSO, potentially through a separate aFRR product.

Accelerating the growth of battery capacity

Finally, the strong business case for aFRR participation may further accelerate the adoption of both residential and large-scale batteries. Passive balancing has served as a steppingstone by improving battery economics in recent years. However, with declining revenues from passive balancing, aFRR provides a timely alternative to maintain profitability and bridge toward a future in which revenue streams from Day-Ahead arbitrage, intraday trading, and self-consumption become more viable. While passive balancing has caused some short-term challenges, the growth of flexible battery capacity is ultimately essential for enabling a reliable and cost-efficient energy transition. From that perspective, these developments should be seen as a positive step forward.

7.5 Contribution to literature

The findings of this research contribute significantly to the existing literature on passive balancing and aFRR bidding strategies for battery energy storage system (BESS) aggregators, addressing the academic gaps identified in Chapter 1. Previous studies on passive balancing, notably by [13] and [14], demonstrated the potential profitability of this strategy compared to day-ahead arbitrage but did not consider the recent market dynamics characterized by increasing occurrences of Regulation State 2 (RS2) and rapid system oscillations. This research specifically extends the understanding of passive balancing under current market conditions, illustrating how RS2 ISPs reduce the revenue potential of passive balancing.

Furthermore, while the literature on aFRR bidding strategies ([15], [16], [17]) explored the profitability of BESS participation in aFRR markets across various European contexts, none directly compared these strategies against passive balancing within the Dutch market's imbalance pricing system. This thesis fills this critical gap by comparing Zonneplan's passive balancing strategy with simulated aFRR bidding strategies using recent historical market data from the Netherlands. It demonstrates that active participation in the aFRR market consistently generates higher and more stable net revenues than passive balancing.

8 Conclusions

This thesis set out to compare the performance of passive balancing and active aFRR participation for an aggregator of home batteries in the evolving Dutch electricity market. By analyzing Zonneplan's passive balancing strategy and simulating realistic aFRR bidding strategies, this research provides clear answers to the guiding sub-research questions below:

SQ1: How does the currently used passive balancing strategy of Zonneplan work and how does it perform under the growing frequency of Regulation State 2 ISPs?

Zonneplan's passive balancing strategy, which involves taking strategic out-of-balance positions based on imbalance price forecasts, initially showed increasing revenue, peaking in August 2024, but consistently declined thereafter. This decline was primarily due to lower activated volumes and rising charging costs. A critical finding was the increasing frequency of Regulation State 2 (RS2) Imbalance Settlement Periods (ISPs). While Ex-Post trading and portfolio advantages largely offset the financial risk of RS2, these periods contributed minimally to overall revenue, suggesting that the growing prevalence of RS2 may be limiting volume opportunities for passive balancing. The inherent inefficiency of passive balancing, with approximately 13% of energy lost due to simultaneous charging and discharging not recognized in settlement, and suboptimal activation patterns, further highlighted its limitations.

SQ2: What are the current trends in the aFRR bidding ladder, prices and volumes?

The analysis of the Dutch aFRR market reveals several important trends. The bidding ladder shows consistently high prices for upward regulation, with sharp increases at higher volumes, while the downward bidding ladder is more volatile, featuring fluctuating minimum prices and greater capacity at low bids, reflecting stronger competition. Since 2022, contracted capacity prices have generally declined due to stabilizing gas markets and more flexible capacity entering the market, while activated volumes have grown, especially after PICASSO's introduction in late 2024. PICASSO has reduced extreme upward price peaks but led to higher average prices, flattening the price curve with more frequent moderate activations. For downward prices, fewer extreme dips occur, and overall prices are higher, meaning BSPs pay more to provide downward capacity. Crucially, the market displays a clear alternating pattern: aFRR upward prices are consistently higher at the beginning and end of the day, making discharge attractive, while frequent negative Downward prices around midday enable profitable charging. This natural cycle of high upward and low downward prices supports battery state-of-charge balancing and makes active participation in aFRR particularly attractive. Furthermore, many price peaks occur during Regulation State 2, offering a structural advantage for active aFRR strategies, as they receive full remuneration, unlike passive balancing.

SQ3: What are possible bidding strategies for Zonneplan to participate in the Dutch aFRR market and how do they perform?

All three considered bidding strategies appear viable for Zonneplan's participation in the evolving Dutch aFRR market. Strategy 1 was tested in two variations using constant bid prices. Strategy 1a applied fixed upward and downward bid prices with a fixed spread and was able to achieve relatively high net revenue with only limited activation, thanks to the efficient capture of high price peaks. Strategy 1b also used constant prices but without a fixed spread, resulting in higher activation and revenue, though with less favorable spreads. Strategy 2, linking bid prices to Day-Ahead market prices with a fixed margin, performed best overall, achieving strong activation levels without long periods of inactivation while maintaining favorable spreads, resulting in the highest net revenue.

Strategy 3, based on Intraday prices, yielded more activated volume but underperformed in terms of net revenue due to narrower price spreads.

The final comparative analysis and the answers to the three sub-questions above, leads to an unequivocal answer to the main research question of this thesis:

How does the performance of aFRR bidding strategies compare to Zonneplan's currently used passive balancing strategy?

Active participation in the aFRR market using a Day-Ahead price-based bid strategy consistently and significantly outperforms the passive balancing strategy in terms of net revenue. This outperformance is driven by higher activation volumes, the ability to operate effectively during all market conditions including Regulation State 2, and superior operational efficiency (no unsettled volume).

Although this research provides a clear answer to the main research question, offers valuable insights for key stakeholders, and addresses a notable gap in the academic literature, it also reveals several areas that require further investigation. The following points outline potential directions for future research.

Suggestions for short term future research

- **Explore multi-market value stacking strategies:**
  Future research should investigate how an aFRR-centered strategy can be combined with participation in the intraday market, which is much larger in volume, more liquid, and thus less prone to saturation effects. This could reduce overall revenue volatility and allow flexible assets to capitalize on price spreads with lower risk. In addition, while this study highlights the financial and system benefits of shifting from passive balancing to active aFRR participation, passive balancing might still be valuable in a broader multi-market strategy. For example, during periods with predictable imbalance directions and low risk of RS2. Using advanced forecasting methods and MILP optimization, future studies could quantify the incremental benefits and operational trade-offs of combining aFRR, intraday arbitrage, and passive balancing to maximize total portfolio revenues.
- **Determine the optimal battery capacity:**
  As highlighted by the sensitivity analysis, the revenue from aFRR bidding strategies is significantly influenced by the level of battery capacity. While lower capacities can still yield substantial revenue, higher capacities allow for increased returns but with diminishing marginal gains. Future research should conduct a more comprehensive cost-benefit analysis to evaluate whether the additional revenue justifies the investment in larger battery capacity. Such an analysis should also account for the optimal capacity in the context of other future applications, such as Day-Ahead Market (DAM) arbitrage or increasing PV self-consumption.
- **In depth aFRR market analysis:**
  Since the revenue potential and the optimal bid strategy are highly sensitive to both the price levels and the activation volumes in the aFRR market, future research should perform detailed econometric or probabilistic analyses of these market parameters. This could include scenario studies under different regulatory frameworks, examining how future changes in imbalance settlement design, PICASSO coupling effects, or grid codes might influence price volatility and aFRR activation. Understanding these dynamics is essential to design bidding strategies that remain robust under various market conditions.
- **Investigate the role of gas plants exiting the aFRR market:**
  With climate targets and the increased competition of BESS accelerating the phase-out of conventional gas-fired power plants that historically provided a substantial share of

balancing reserves, there is a growing risk of insufficient upward and downward reserves during prolonged periods of high system stress. Future studies could explore how the exit of conventional units might affect aFRR price spikes, activation patterns, or lead to extreme moments of scarcity. Such research could also assess the implications for battery business models, which might benefit from scarcity pricing but also face operational risks if frequent deep discharges are required to support the grid under such stressed conditions.

- **Study market saturation effects:**
  The aFRR market is relatively small in total contracted and activated volume. As more BESS aggregators and large-scale batteries enter the market, saturation effects are likely. Future research should quantify how increasing penetration of flexible assets affects prices, the frequency of activations, and the achievable revenues per unit of capacity. Agent-based simulations or market equilibrium models could be useful here to explore tipping points where additional storage capacity starts to significantly reduce profitability due to intensified competition.

In closing
This research highlights a critical turning point for aggregators of home batteries and large-scale battery energy storage systems. The potential of passive balancing appears to be decreasing, driven by the strategy's own impact on the market.

The path forward lies in active, system-supportive market participation. For aggregators like Zonneplan, embracing the operational challenge of the aFRR market is not just a strategic option but a financial and systemic necessity. By doing so, they can unlock potentially higher returns for their customers and transform their aggregated battery portfolios into a truly valuable asset for ensuring a stable and reliable energy transition.

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Appendix

Appendix A: Introduction (Chapter 1)

Literature selection process

This section describes the literature selection process used to identify the academic knowledge gap that proves the relevance of this study. A flow diagram outlines the process of literature selection, including identification, screening, and eligibility. Each step is explained, starting from the formulation of targeted search strings. The section also includes two tables of selected studies and gives an overview the existing relevant academic literature.

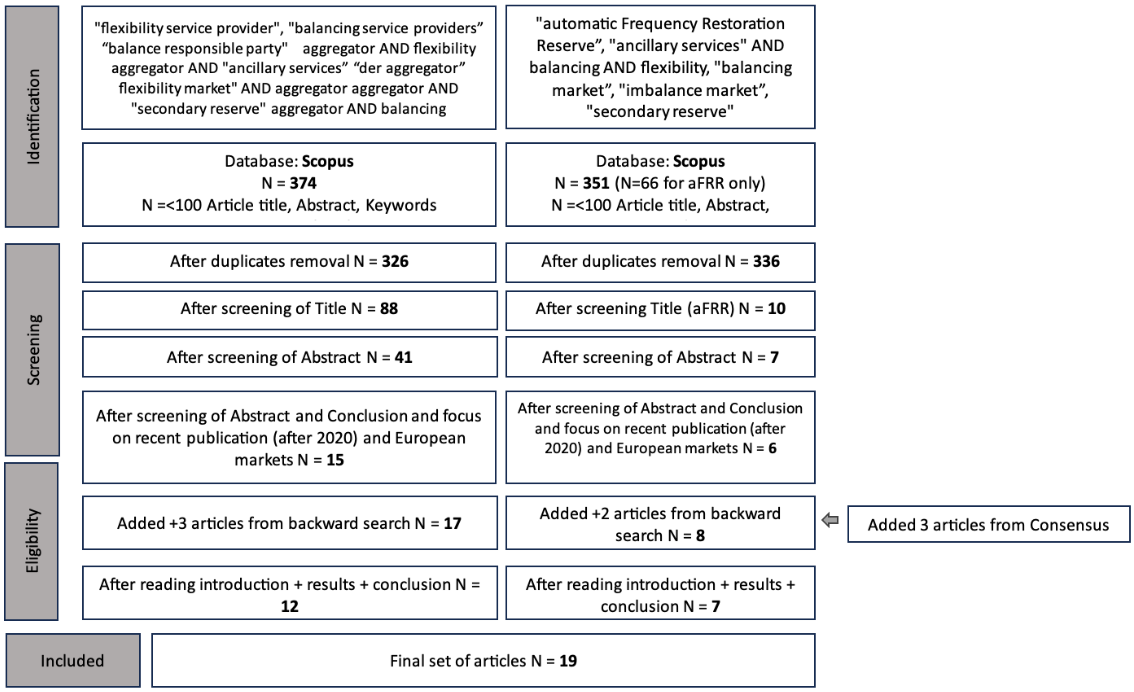

Figure 41: Literature selection flow diagram

Identification

The literature selection began by developing relevant search strings that combined keywords related to aggregators, flexibility service providers, aFRR, and ancillary services more broadly. To maintain focus and structure, two distinct sets of search strings were used. The first set aimed to find literature specific to the emerging role of DER aggregators in balancing markets, while the second set had a broader scope, targeting literature on balancing markets with an emphasis on aFRR.

Given the absence of a standardized term for DER or BESS aggregators, both "aggregator" and "flexibility service provider" were combined with related keywords. For aFRR, synonyms such as "automatic frequency restoration reserve" and "secondary reserve" were included to ensure completeness. Searches were conducted using the Scopus database, with results filtered by the fields article title, abstract, and keywords. To maintain a manageable quantity of results, the aim was to limit each query to a maximum of 100 articles. If a query exceeded this number, it was restricted to the article title field for greater specificity.

The reference management software Mendeley was used to import, organize, and manage the collected literature. This identification process produced an initial set of 758 articles.

Screening

In the screening phase, duplicates were removed using Mendeley, reducing the selection to 662 unique articles. Titles were reviewed to assess relevance, and articles were excluded if they focused on local DSO-level balancing services, proposed integrated TSO-DSO frameworks, or addressed only FCR or mFRR. The goal was to maintain a balance between qualitative and modeling studies and to focus on papers discussing aggregated BESS. This step led to a refined selection of 48 articles.

If the relevance of an article was not clear from the title, the abstract was evaluated using the same criteria. This step reduced the selection to 21 relevant sources.

Eligibility

To ensure completeness, a backward citation search was performed on the selected articles, which added 5 more relevant papers. A final check using the Consensus AI tool ensured that no key studies were excluded. The introduction, methodology, and conclusion of each remaining article were thoroughly reviewed to assess both relevance and quality. A few articles were removed during this final review, resulting in a final selection of 19 articles.

The selected articles, as summarized in the analytical tables below, were examined in more detail. Table 15 indicates whether the studies are conducted from an aggregator perspective and identifies which markets are included in the strategies modeled or analyzed, such as aFRR, FCR, DAM, and IDM, which are often combined. Furthermore, Table 16 shows whether the studies specifically focus on distributed energy resources, and if battery energy storage systems (BESS) and electric vehicles (EV) are explicitly considered. Lastly, it provides the geographical focus of each study. The studies that are discussed in depth in the literature review are highlighted in grey. Other studies included in the tables serve primarily to provide additional context.

Table 15: Final literature selection from aggregator focused search

Titel	Publ. year	Author(s)	Aggregator	aFRR	FCR	DAM	IDM	DERs	BESS	EV	Geographical focus	Ref.
Robust market-based battery energy storage management strategy for operation in European balancing markets	2024	Baltputnis K., Broka Z., Cingels G., Sīlis A., & Junghāns G.	n	y	y	y	y	n	y	n	EU / Baltic	[52]
BESS Revenue Stacking Optimization in the Italian Market by means of the MUSST Stochastic Tool	2022	Canevese, S., Gatti, A., & Siface, D.	n	y	y	y	n	n	y	n	Italy	[53]
Impact of Imbalance Settlement System Design on Risk-Averse Energy Storage	2020	Herre, L.	y	n	n	y	n	n	y	n	Sweden	[54]
Electricity market equilibria analysis on the value of demand-side flexibility portfolios' mix and the strategic demand aggregators' market power	2024	Khaksari, A., Steriotis, K., Makris, P., Tsaousoglou, G., Efthymiopoulos, N., & Varvarigos, E.	y	n	n	y	n?	y	y	Y	-	[55]
Optimizing bidding strategies for the German secondary control reserve market: The impact of energy prices	2018	Loesch, M., Rominger, J., Nainappagari, S., & Schmeck, H.	y	y	n	n	n	n	n	n	Germany	[56]
An optimized trading strategy for an energy storage systems aggregator in an ancillary service market	2023	Lokhande, S., Bichpuriya, Y., Kulkarni, A. A., & Sarangan, V.	y	y	y	n	n	y	y	n	France	[18]
Optimal Participation of RES Aggregators in Energy and Ancillary Services Markets	2023	Marneris, I. G., Ntomaris, A. V., Biskas, P. N., Baslis, C. G., Chatzigiannis, D. I., Demoulias, C. S., Oureilidis, K. O., & Bakirtzis, A. G.	y	n	y	y	n	y	n	n	Greece	[57]

Aggregator's business models in residential and service sectors: A review of operational and financial aspects	2021	Okur, O., Heijnen, P., & Lukszo, Z.	y	y	y	y	y	y	y	y	Literature review	[58]
Stacked Revenues Maximization of Distributed Battery Storage Units Via Emerging Flexibility Markets	2022	Steriotis, K., Sepetanc, K., Smpoukis, K., Efthymiopoulos, N., Makris, P., Varvarigos, E., & Pandzic, H.	y	y	y	y	n	y	y	n	Hungary	[19]
Strategic Implicit Balancing With Energy Storage Systems via Stochastic Model Predictive Control	2023	Smets, R., Bruninx, K., Bottieau, J., Toubeau, J., & Delarue, E.	y	y	n	y	n	n	y	n	Belgium	[13]
Modelling the economic feasibility of distributed flexibility assets in the Dutch electricity markets	2022	De Weerd, S., Gibescu, M., De Leeuw, M., Van Haperen, J., & Siebenga, B.	y	y	n	y	n	y	y	n	Netherlands	[14]

Table 16: Final literature selection from aFRR focused search

Titel	Publ. year	Author(s)	Aggregator	aFRR	FCR	DAM	IDM	DERs	BESS	EV	Geographical focus	Ref.
Assessing flexibility options in electricity market clearing	2023	Koltsaklis, N.E., Knápek, J.	n	y	y	y	n	y	y	y	Europe	[59]
Wind-Battery Pool Optimal Bidding in German Energy and Secondary Control Reserve Markets	2024	Mancini, G., Delikaroglou, S., Stai, E., Stanojev, O., & Hug, G.	n	y	n	y	n	n	y	n	Germany	[16]
Bid strategy for battery storage systems in the secondary control reserve market	2020	Merten, M., Olk, C., Schoeneberger, I., & Sauer, D. U.	n	y	n	y	y	n	y	n	Austria and Germany	[15]
Economic evaluation of battery storage systems bidding on day-ahead and automatic frequency restoration reserves markets	2021	Nitsch, F., Deissenroth-Uhrig, M., Schimeczek, C., & Bertsch, V.	n	y	n	y	n	n	y	n	Germany	[20]
Revenue stacking of BESSs in wholesale and aFRR markets with delivery guarantees	2024	Paredes, Á., & Aguado, J. A.	n	y	n	y	n	n	y	n	Belgium	[17]
Distributed energy resources and the organized balancing market: A symbiosis yet? Case of three European balancing markets	2019	Poplavskaya K. de Vries, L.	y	y	y	n	n	y	n	n	Europe	[42]
Strategies for electric vehicle bidding in the German frequency containment and restoration reserves market	2024	Seo, M., Jin, Y., Kim, M., Son, H., & Han, S.	y	y	y	y	n	n	y	y	Germany	[60]

Appendix B: Background (Chapter 2)

Table 17: Minimum level of contracted aFRR capacity for The Netherlands [61]

	aFRR (minimum) (MW)	
Period	**Up**	**Down**
2019- Q1-Q2	425	425
2019 Q3-Q4	385	385
2020 Q1-Q2	310	310
2020 Q3-Q4	310	310
2021 Q1-Q2	300	290
2021 Q3-Q4	290	290
2022 Q1-Q2	310	310
2022 Q3-Q4	323	324
2023 Q1-Q2	324	352
2023 Q3-Q4	324	362
2024 Q1-Q2	350	350
2024 Q3-Q4	373	405
2020 Q1-Q2	454	496

Appendix C: Passive Balancing (Chapter 4)

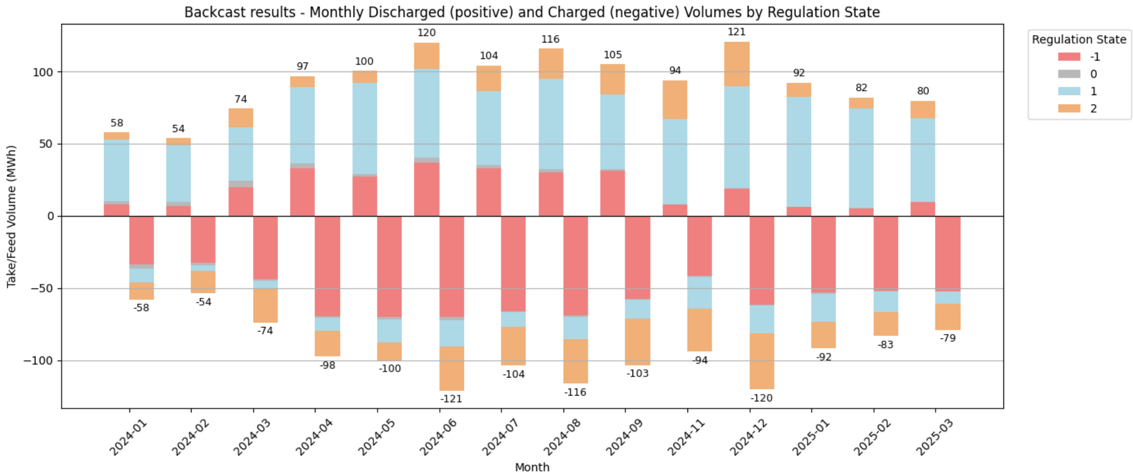

Figure 42: Passive balancing Results - Monthly Discharged (positive) and Charged (negative) Volumes by regulation state including unsettled volume (Jan 2024 – March 2025)

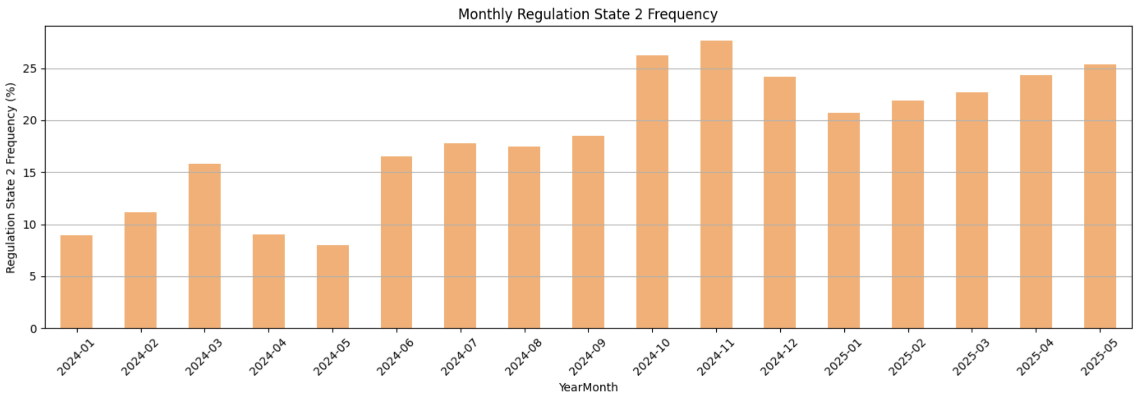

Figure 43: Monthly Regulation State 2 distribution (%) (Jan 2024 – May 2025)

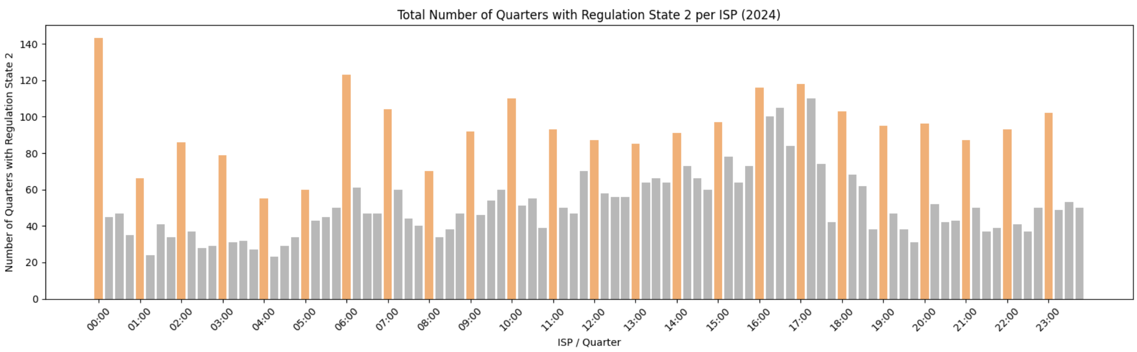

Figure 44: Total frequency of Regulation State 2 ISPs per ISP (2024)

Figures 45 and 46 below show the Price shortage and Price Surplus for August 2024. This month shows an extreme frequency of price spikes, which explains the high revenue during this month.

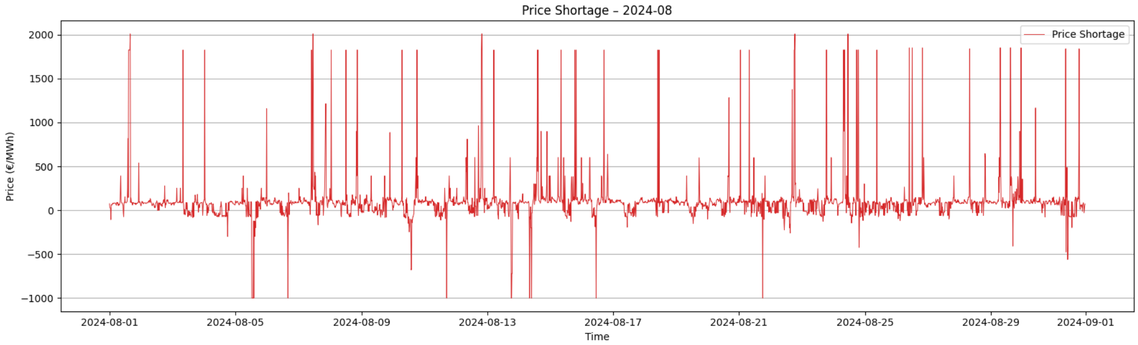

Figure 45: Price Shortage 2024-08

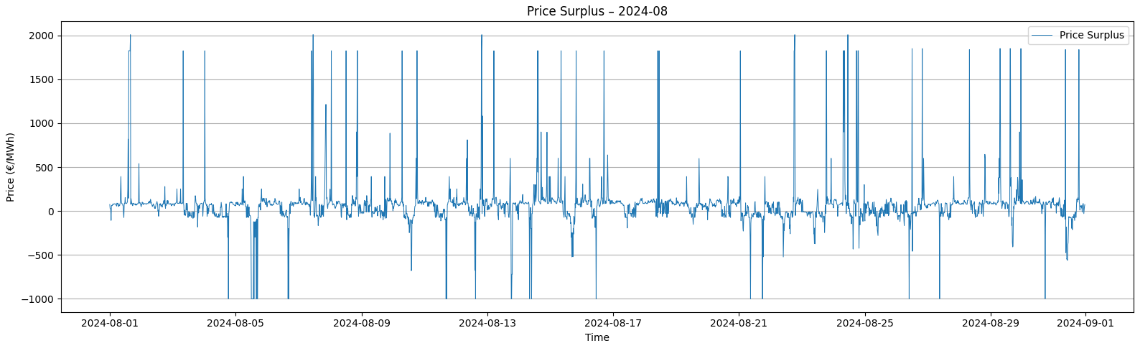

Figure 46: Price Surplus 2024-08

Figures 47 and 48 below show the Price shortage and Price Surplus for March 2025. This month shows a considerably lower frequency of price spikes, which explains the lower revenue of this month. Additionally, it underscores the importance of effectively capturing these price peaks.

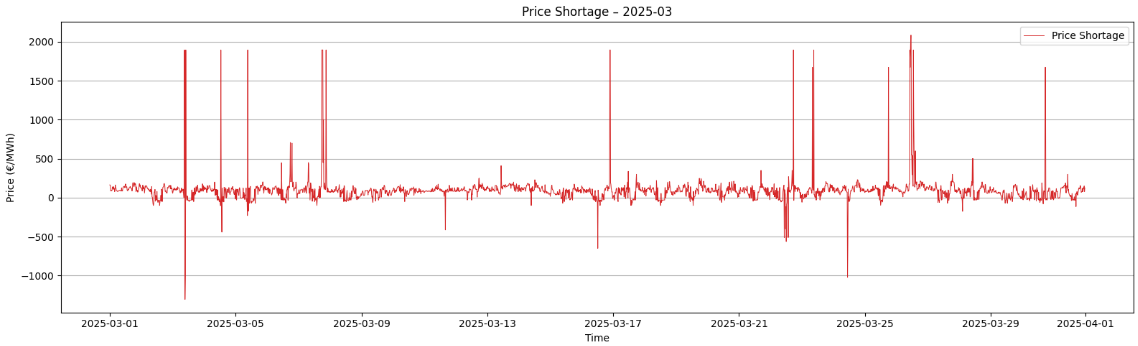

Figure 47: Price Shortage 2025-03

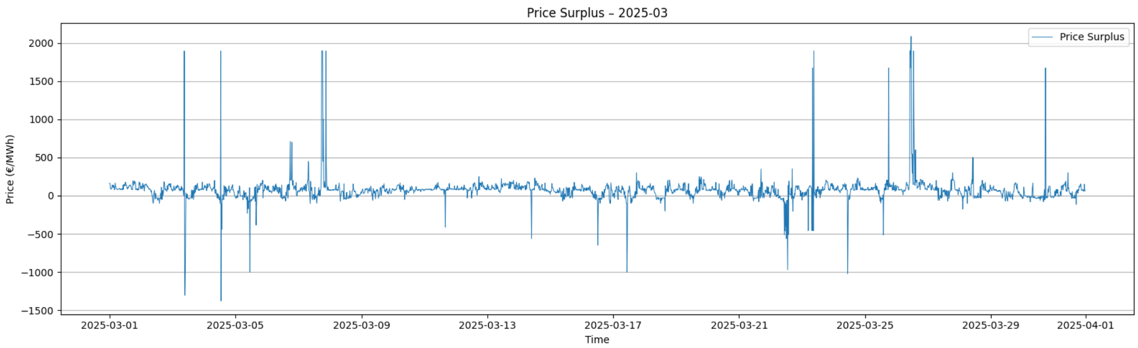

Figure 48: Price Surplus 2025-03

Table 18: Monthly Passive balancing difference in Settled and Total absolute volume

Month	Absolute Settled Volume (MWh)	Total Absolute Volume (MWh)	Δ %
2024-01	107	116	-8%
2024-02	98	107	-9%
2024-03	125	148	-16%
2024-04	166	194	-15%
2024-05	172	200	-14%
2024-06	194	241	-20%
2024-07	171	208	-18%
2024-08	186	232	-20%
2024-09	168	208	-19%
2024-11	161	188	-14%
2024-12	204	241	-16%
2025-01	173	184	-6%
2025-02	158	165	-4%
2025-03	153	159	-4%
Total / average	2234,62	2592,12	-13%

Appendix D: Simulations (Chapter 6)

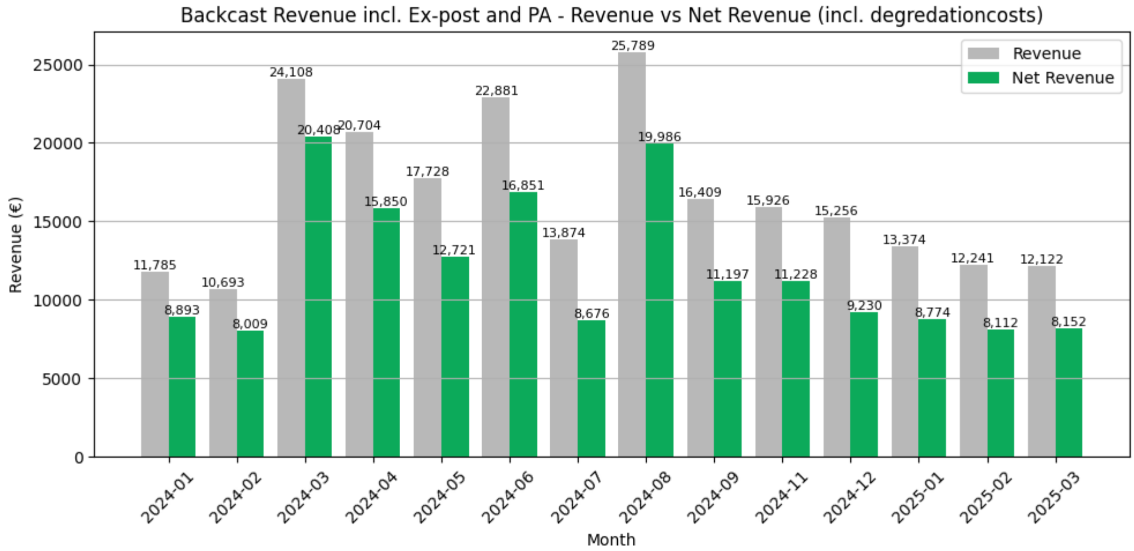

Figure 49: Monthly passive balancing Net Revenue 1 MW / 2 MWh – Excl. vs Incl. Ex-post trading and internal and external portfolio advantages (Jan 2024 – March 2025)

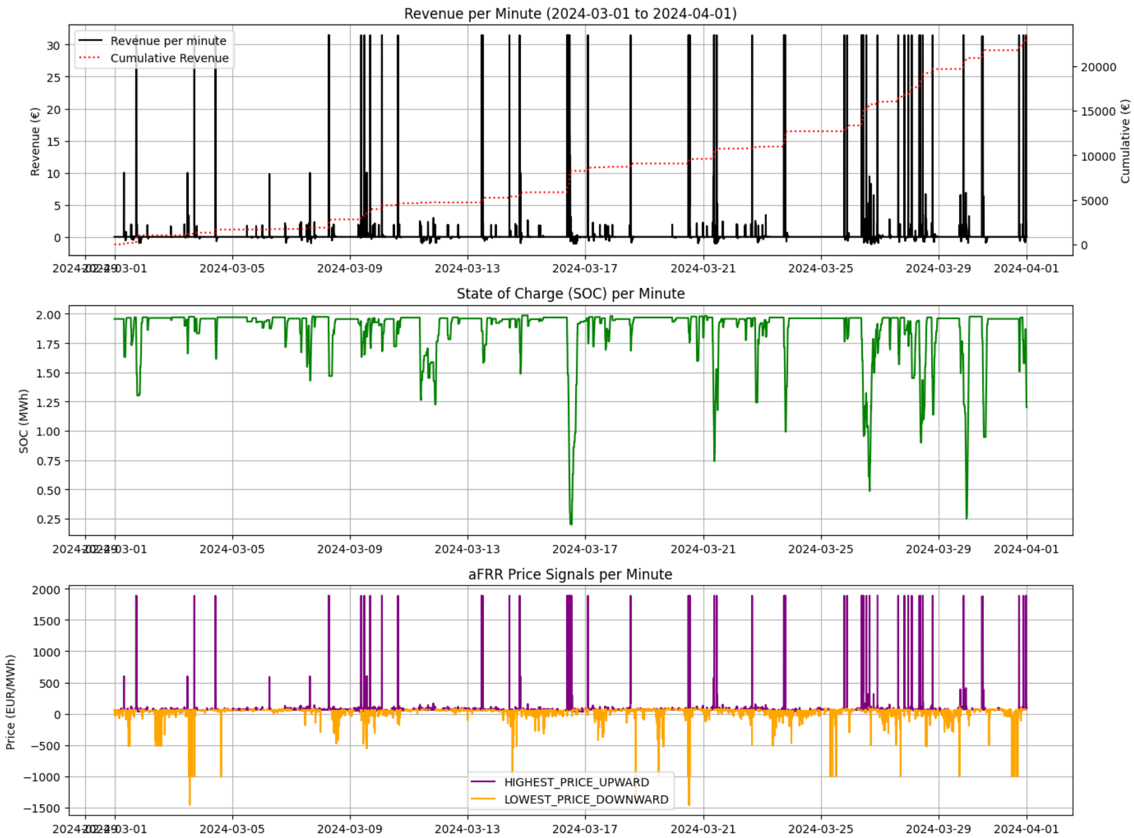

Figure 50: Simulation output Bid Strategy 1b - Revenue and State of Charge per minute including minutely aFRR upward and downward prices (March 2024)

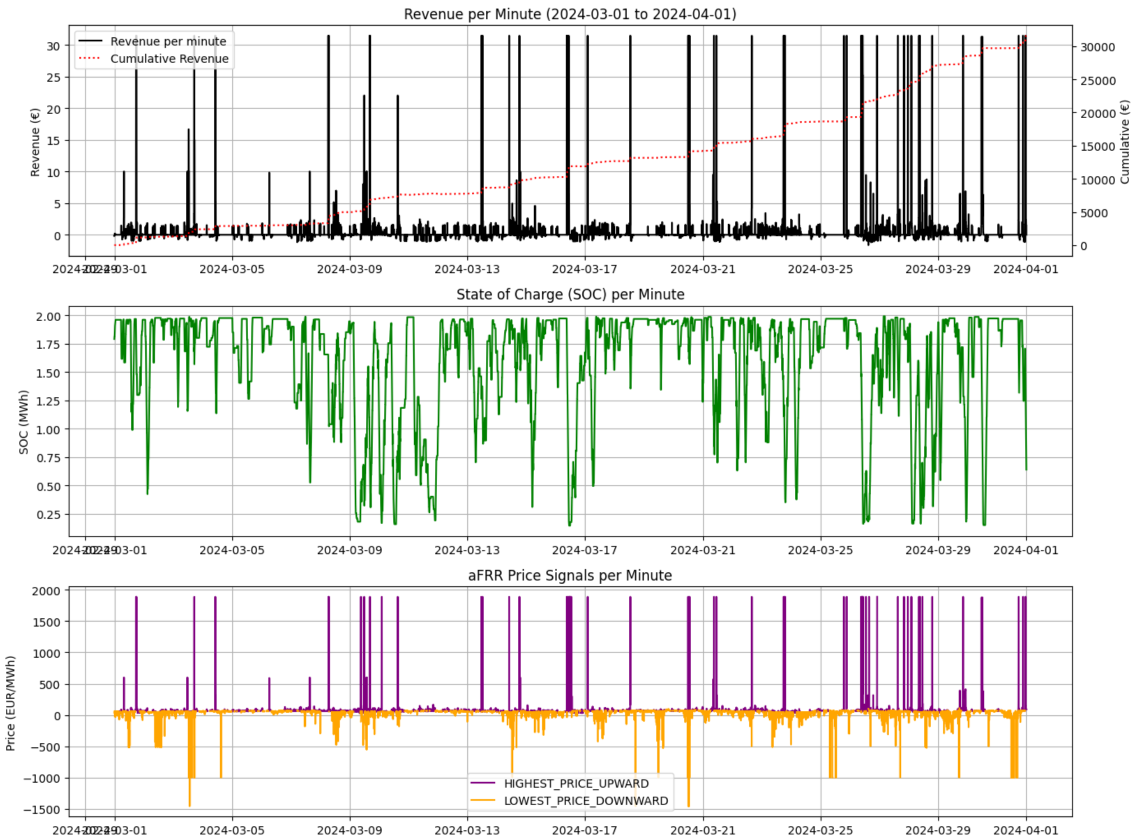

Figure 51: Simulation output Bid Strategy 2 - Revenue and State of Charge per minute including minutely aFRR upward and downward prices (March 2024)

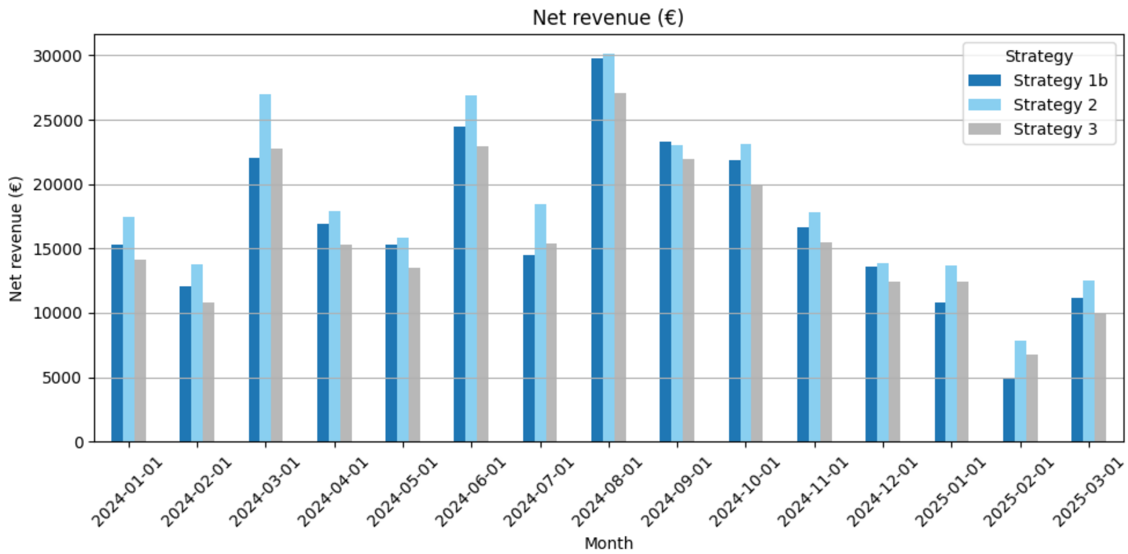

Figure 52: Monthly Net Revenue comparison of Bidding strategies 1b, 2 and 3